Evaluating the Competitive Ability of Semi-leafless Field Pea (*Pisum sativum* L.)

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Abstract

Field pea (*Pisum sativum* L.) is an important grain legume in western Canada. Growers can, however, be reluctant to include pulse crops such as field pea in their rotation because they are poor competitors with weeds. This thesis research was conducted to determine whether competitive differences exist among semi-leafless field pea cultivars and to determine the mechanism(s) driving competitive differences. Cultivars included in the studies were chosen on the basis of varying seed size and vine length, which are traits known to confer competitive ability. Differences in competitive ability were identified among cultivars as yield loss ranged from 9% to 31% and 14% to 31% for model weed seed return. However, cultivars were inconsistent in their competitive ranking as cultivars typically performed well for one metric, but not both. None of the traits measured in this study correlated with competitive ability. The greenhouse research was unable to identify the mechanism responsible for these competitive differences. Focal pea plants generally responded to the presence of below-ground neighbours by allocating more resources to shoot production. Therefore, semi-leafless field pea cultivars exhibit differences in below-ground responses to neighbours and it may be useful to include this as part of the selection criteria in breeding programs.

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Dedication

I would like dedicate this work to all four of my grandparents (Mike and Jean Iluk and Alfred and Eva Jacob) who fortunately, all are still alive and well despite their age. They taught me how to work hard and appreciate what you have. I also want to quote my great grandmother, who lived to be 96 years old "a little bit of hard work never hurt anyone."

Table of Contents

List of Tables

List of Figures

List of abbreviations

AC	Ability to Compete
a.e.	Acid Equivalent
a.i.	Active Ingredient
AWC	Ability to Withstand Competition
cv	Cultivar
HSD	Honestly Significantly Different
R:S	Root : Shoot
Y_{wfp}	Yield of Weed-Free Plots
Y_{wp}	Yield of Weedy Plots

1.0 Introduction

Canada is the world's largest producer and exporter of field peas. Saskatchewan accounts for 72% of Canada's field pea crop, while production in Alberta and Manitoba comprise the remaining 28% (Saskatchewan Pulse Growers, 2009; Saskatchewan Ministry of Agriculture, 2013). One of the reasons that field pea is popular is because it has the ability to fix its own nitrogen (Przednowek et al., 2004), and to use water more efficiently than most crops (Beckie and Brandt, 1997; Miller et al., 2002). These rotational benefits make it a useful crop in almost any rotation as additional nitrogen and water will benefit the following crop, while also reducing associated production costs.

Pulse crops such as field pea are vulnerable to many pests, including weeds. Weed competition is detrimental to field pea yield as weeds compete vigorously with the crop. For example, pulse crops, unlike cereal and oilseed crops are the most susceptible crops to weed interference, with yield losses of 20% to 40% commonly observed (Wall et al., 1991). However, yield losses as high as 80% have been reported (Boreboom and Young 1995). This lack of competitive ability leads to a reluctance among growers to include pulse crops in their rotation. Including competitive cultivars in crop rotations is an essential part of integrated weed management (Dew, 1972) and could help growers improve field pea production.

Developing more competitive field pea cultivars also may reduce herbicide dependence (McDonald, 2003). Variation in the competitive ability between crop cultivars has been reported frequently (Wall and Townley-Smith, 1996; Tepe et al., 2005; Willenborg et al., 2005a; Watson et al., 2006; Spies et al., 2011). Field pea is no exception as McDonald (2003) and Wall and Townley-Smith (1996) showed that tall field pea cultivars yield higher than short and medium height cultivars under weed competition. Harker et al. (2008) showed that unsprayed normal leaf cultivars of field pea can yield as much or more than semi-leafless cultivars that have received a herbicide application. Similar research also showed that normal leaf cultivars were more competitive with wild mustard (*Sinapsis arvensis* L.) than semi-leafless cultivars (Wall et al., 1991). This shows that field pea can be a competitive crop if normal-leaved cultivars are grown and weed control is optimal. However, most of the field pea production on the Northern Great Plains is comprised of semi-leafless field pea cultivars due to their lodging resistance, ease of harvest, and reduced fungal disease severity.

Since traits such as height and leaf area are critical to competitive ability, and semi-leafless field pea cultivars vary little in canopy height and possess tendrils as opposed to leaflets, there may be few competitive differences between cultivars and hence, little variation between traits on which to make selections to improve competitive ability. Therefore, the objective of this thesis was to determine if there are competitive differences among semi-leafless field pea cultivars, and if so, to determine the mechanism behind these competitive differences. This thesis addressed those objectives through two studies. The first study evaluated the ability of semi-leafless cultivars to compete with and to withstand weed competition in an attempt to assess competitive differences among the cultivars, as well as to find above-ground traits that correlated with improved competitive ability. The second study explored the relative importance of above- and below-ground competitive ability of semi-leafless field pea cultivars under greenhouse conditions.

2.0 Literature Review

2.1 Field pea production

Field pea (*Pisum sativum* L.) is an important pulse crop to the Saskatchewan economy. In 2010, production was estimated at approximately 1.9 million tonnes with an export value totalling $870 million (Saskatchewan Ministry of Agriculture, 2011). Canada plays an important role as the world's largest producer and exporter of field peas. Saskatchewan's production accounts for 72% of Canada's field pea crop, while production in Alberta and Manitoba comprise the other 28% (Saskatchewan Pulse Growers, 2009). Canada, USA, France, Australia, and the Ukraine are the world's main exporters of field peas, while the main importing countries are India, China, Bangladesh, Belgium, Spain, Holland and Columbia (McVicar et al., 2009).

Field pea was one of the first crops cultivated by man over 9,000 years ago, and has been grown in Europe for several thousand years (Zohary and Hopf, 2002). Archaeological evidence shows that field pea dates back to the Stone Age more than twenty thousand years ago (Pulse Australia Limited, 2009). The centre of origin for this crop is Middle Eastern countries including Jordan, Lebanon, Iran, Iraq, Israel, Syria, and Turkey (McVicar et al, 2009).

2.1.1 Field pea rotational benefits

Field pea is an important crop in crop rotations, as it has its own unique benefits such as the ability to fix its own nitrogen (Przednowek et al., 2004) and to use water more efficiently than other crops (Beckie and Brandt, 1997; Miller et al., 2002). Research has shown that field pea provides a residual nitrogen benefit to subsequent crops. Approximately 12 to 27 kg N ha^{-1} can be available for crops following field pea (Beckie and Brandt, 1997). Field pea is very efficient at using water and therefore, leaves more soil moisture for following crops (Miller et al., 2002). Zain et al. (1983) documented that both a normal leaf and a semi-leafless field pea cultivar are similar in water use efficiency. Moreover, irrigation caused the water use efficiency to decline in both cultivars in comparison to non-irrigated production. These rotational benefits make field pea a useful crop in almost any crop rotation It is the only pulse crop that can be successfully grown in all soil zones of Saskatchewan (McVicar et al., 2009).

2.1.2 Field pea leaf type

Field pea cultivars grown in western Canada are divided into two leaf types: normal leaf and semi-leafless. A Normal leaf cultivar leaf structure consists of stipules, petiole, leaflets, and tendrils, whereas semi-leafless cultivars have leaflets replaced by tendrils (McKay et al., 2003; Schatz and Endres, 2003; Spies, 2008). In the early 1980s, the first semi-leafless pea cultivar, afaf StSt was released for commercial use in England (Martin et al., 1994). Today, most field pea grown in conventional agriculture are semi-leafless, whereas normal leaf field pea cultivars dominate organic crop production because of their ability to suppress and compete with broadleaf weeds and grassy weeds (Liebman and Robichaux, 1990; Wall et al., 1991; Wall and Townley-Smith, 1996; McDonald, 2003; Harker et al., 2008; Spies, 2008).

Semi-leafless field pea was developed mainly for their lodging resistance, and that characteristic is largely responsible for their popularity (Heath and Hebblethwaite, 1985b). The leaflets in semi-leafless field pea cultivars are replaced by tendrils, which results in reduced leaf area, but improved lodging resistance due to the tendrils intertwining and providing vertical support for plants (May et al., 2003). This reduction in lodging assists in improving ease of harvest (Martin et al., 1994). Snoad (1974) showed that most semi-leafless cultivars have a similar yield to normal leaf types. Though yield is similar between semi-leafless and normal leaf cultivars, the yields of normal leaf cultivars have been shown to be slightly lower than semi-leafless cultivars in the absence of weed competition (Snoad, 1974). Research also has shown that in semi-leafless cultivars, reduced height and leaf area contribute to greater light interception and better canopy aeration compared with normal leaf cultivars (Heath and Hebblethwaite, 1985b; Cote et al., 1992). The commercial importance of semi-leafless cultivars is largely due to their ability to endure disease pressure, reduced lodging, and their unique canopy structure that permits more light and canopy aeration (Cote et al., 1992). These improvements make semi-leafless cultivars agronomically superior to normal leaf cultivars, making them a popular choice in conventional and organic agriculture.

2.1.3 Field pea seed classes

Field pea market classes in production in western Canada include yellow, green, maple, marrowfat, dun and forage. Yellow field peas dominate production due to a 10-15% greater yield over green field peas, but typically return a lower price than green peas (Saskatchewan Pulse Growers, 2009). Green field peas are prone to bleaching when suboptimal weather conditions exist (rain and sun) prior to harvest, but sell for a higher price (Saskatchewan Pulse Growers, 2009). The primary use for both yellow and green cultivars is food markets, while both can also utilized as feed. Maple peas often find use in feed for racing pigeons (McVicar et al., 2009), and marrowfat peas are used as a specialty food snack in Asia (McVicar et al., 2009). Dun field peas are also sold for human consumption, particularly in India after dehulling of the seed (Warkentin, 2012). Forage pea cultivars are typically grown in mixtures with annual cereals such as barley, oat or triticale, then cut when the cereal reaches soft dough stage and used for green feed or silage.

2.2 Plant Competition

Plant competition can be defined as one plant directly affecting the growth of another by accumulating resources available to both plants (Harper, 1977). Competition can also be defined as the individual capacity of a plant species to disrupt the development and/or existence of plants pertaining to another plant species (Tilman, 1997). Williamson (1972) noted that competition results in the demise of the less competitive species. Competition is different than interference, which includes competition and allelopathy (Zimdahl, 2004). The most competitive plant species will be able outcompete neighbouring plants for resources (Donald, 1963; Radosevich et al., 1997), have a high nutrient acquisition rate, and be efficient at metabolizing nutrients (Grace, 1990). Competition above-ground (between shoots for sunlight) and below-ground (between roots for water and nutrients) occurs between plants. Competition above-ground or below-ground may be more advantageous to certain plant species, helping them to better exploit resources from their neighbours and making them a successful competitor (Pavlychenko and Harrington, 1934).

Two types of competition occur between plants: interspecific and intraspecific competition. Interspecific competition occurs between plants of different species, whereas intraspecific competition occurs between plants of the same plant species (Donald, 1963). Ecologists classically define interspecific competition as an interaction among dissimilar plant species such that increased biomass and plant density of one plant species has the opposite result of reducing the growth rate, density, and biomass of another plant species (Tilman, 1997).

Competition between field pea plants is, therefore, an example of intraspecific competition; competition between field pea and other species is interspecific competition.

Plant competition takes place between two or more plants in direct competition for resources, including sunlight, water, and nutrients. Competition for resources occurs when the supply of a resource cannot meet the demand of plants, resulting in the more competitive plant species acquiring disproportionately more of the available resource (Berkowitz, 1988). Competition is prevalent among plants as they grow as part of a plant community in an ecosystem, or in intraspecific or interspecific plant associations (Radosevich et al., 2007; Benaragama, 2011).

Crop competitive ability is a term used to measure how competitive a crop is with weeds. Competitive effect, competitive response, and a combination of both are the crop's reaction to weed competition (Callaway, 1992; Jordan, 1993). Competitive effect is a response wherein the crop suppresses weed growth and reproduction (Goldberg, 1990; Goldberg and Landa, 1991) and is measured by a reduction in weed seed production, biomass, and germination (Jordan, 1993). Competitive response is the ability of the crop to avoid suppression or respond to competition, and is observed as the maintenance of yield and biomass under competition with weeds (Jordan, 1993). Christensen (1995) reported that among seven barley cultivars, the most suppressive variety permitted 48% less weed dry matter than the average weed dry matter of all varieties. Among 29 barley cultivars, cv. Virden only allowed 10% weed seed production, while 83% was observed for cv. Peregrine (Watson et al., 2006). A wheat and wild oat competition study by Sodhi and Dhaliwal (1998) found that wheat genotype 'PBW343' applied excess canopy pressure due to its height, leaf area index, biomass, and light interception. This resulted in a 14% reduction in wild oat dry matter accumulation. In contrast, competitive response to weed competition is the ability to maintain yields under competition. For example, under weed competition, cv. Peregrine barley exhibited a yield loss of 79% compared with only a 6% yield loss in cv. Virden barley (Watson et al., 2006). Among winter wheat varieties competing with downy brome, cv. Centura suffered a 9% yield loss, whereas cv. Bennett exhibited a 41% yield reduction (Challaiah et al., 1986).

2.3 Crop and weed species differences in competitive ability

Field crops exhibit large variation in their competitive ability. Barley (*Hordeum vulgare* L.) (Pavlychenko and Harrington, 1934; Bell and Nalewaja 1968b; O`Donovan, 1985), rye (*Secale cereale* L.) (Pavlychenko and Harrington, 1934; Melander, 1993), and oat (*Avena sativa* L.) (Lemerle et al., 1995; Seavers and Wright, 1999) are the most competitive field crops. Field pea is regarded as a non-competitive crop, exhibiting a 100% yield loss due to competition from annual ryegrass (*Lolium rigidum* L.) (Lemerle et al., 1995) and a 35% yield loss due to competition with quackgrass (Elymus repens L.) (Melander, 1993). Pavlychenko and Harrington (1934) were pioneers in crop-weed competition, and they ranked crops by their competitive abilities with weeds. Following exposure of crops to a variety of weed species, barley and rye were recognized as the most competitive crops. Wheat (*Triticum aestivum* L.) and oat followed, while flax (*Linum usitatissimum* L.) was deemed the least competitive crop (Pavlychenko and Harrington 1934).

Other research, however, has produced contrasting results. In North Dakota, Bell and Nalewaja (1968b) provided adequate nitrogen and phosphorus for plant growth. The studied fertility-altered competition; unfertilized plots of barley and wheat suffered 26 and 27% yield losses compared with fertilized plots, where 9 and 41% yield reductions were observed. In

Alberta O'Donovan (1985) grew wheat and barley in competition with wild oat on silty loam and sandy loam soils and fertilized to soil test recommendations, finding that barley was more competitive than wheat. In Denmark, Melander (1993) reported that rye was most competitive, followed by wheat, barley, oilseed rape, and pea. Yet other research in Australia has reported that oat was the most competitive crop, followed by rye, triticale (x *Triticoscale*), oilseed rape, spring wheat, spring barley and field pea (Lemerle et al., 1995). Thus, the competitive ability of a crop is not definite and can vary with environmental conditions and competing weeds species (Cousens and Mokhtari, 1998, Wildeman, 2004).

2.4 Genotypic differences in competitive ability

Regardless of crop type, Froud-Williams (1997) state that a competitive crop genotype will typically include specific characteristics such as early establishment, large seed size, the ability to tiller or branch, a height advantage, and the ability to capture photosynthetically active radiation. Callaway (1992) noted that traits such as rapid seedling emergence and relative growth rate, large leaf area index, a dense canopy, branching, biomass, and a high rate of nutrient use are critical to a competitive genotype.

Crop genotypes can differ in their competitive abilities (Wildeman, 2004). Among 29 barley cultivars tested, cv. Virden (tall) was found to have the greatest crop tolerance and weed suppression. The cultivar Peregrine (semi-dwarf) was ranked as the cultivar with the least crop tolerance and weed suppression (Watson et al., 2006). Spies et al. (2011) reported that field pea variety 40-10 (normal leaf) consistently supressed weed growth better than eight semi-leafless cultivars, while Challaiah et al. (1986) found that the winter wheat cultivar 'Turkey' was more competitive with downy brome (*Bromus tectorum* L.) than 'Centurk 78'. Research conducted by

McDonald (2003) tested 21 field pea genotypes in the presence and absence of ryegrass and wheat. Tall genotypes were better competitors, and leaf type was not a direct contributor to competitive genotypes.

2.5 Traits associated with competitive ability

Some common characteristics are shared among competitive cultivars, regardless of crop species. These include large seed size (Boyd et al., 1971; Bockus and Shroyer, 1996; Froud-William, 1997; Willenborg et al., 2005b), early vigorous growth (Lemerle et al., 1996, Froud-Williams, 1997), large number of tillers (Appleby et al., 1976; Moss, 1985; Challaiah et al., 1986; Lemerle et al., 1996; Froud-Williams, 1997), tall stature (Allan et al., 1962; Appleby et al., 1976; Challaiah et al., 1986, Gaudet and Keddy, 1988; Huel and Hucl, 1996; Seefeldt et al., 1999; McDonald, 2003; Murphy et al., 2008; Zerner et al., 2008), lax leaves (Tanner et al., 1966; Jennings and Aquino 1968, Smith, 1974), and high leaf area (Kawano et al., 1974; Garrity et al., 1992; Dingkuhn et al., 1999; Fischer et al., 2001; Semere and Froud-Williams, 2001).

2.5.1 Above-ground competition

Crops exhibit different traits that influence their competitiveness, including plant height and leaf area. The presence or absence of weeds also influences this. In the presence of weeds, Donald and Hamblin (1976) recognized certain traits (both above- and below-ground) that are influential to a cereal crop's competitiveness. For below-ground competitiveness, the ability to establish a root system in a timely manner and to continue root growth at a rapid rate are important (Dunbabin, 2007). Above-ground competitiveness involves multiple traits such as a greater plant height, as well as numerous, large and horizontal leaves, and a canopy architecture that intercepts maximum solar radiation with minimal light penetration through the plant canopy.

Competition for solar radiation is a complicated and intense process between crops and weeds. Canopy structure in mixtures and monocultures of wheat and wild oat has demonstrated that slight modifications in morphology or canopy structure holds prominence over differences in photosynthetic characteristics in determining how light is shared (Beyschlag et al., 1990). Research conducted by Cudney et al. (1991) found that wild oat established the majority of its leaf area near the top of the crop canopy, where light is plentiful. Yield losses were affected by wild oat suppression treatments: 9% yield loss was observed when wild oats removed at stem elongation, 28% loss when wild oats were clipped at the top of the wheat canopy, 33% loss when wild oats removed at anthesis, and 44% loss with no suppression. Barnes et al. (1990) studied how wild oat changes the canopy structure of wheat grown in both mixtures and monocultures. In monocultures, similarity in leaf area indices was noticed until mid-season, when the oat surpassed the wheat (Barnes et al., 1990). As the season progressed, wheat leaf area index declined from 59% in the upper half of the mixed crop canopy to 49% mid-season and 43% late-season (Barnes et al., 1990). These results show how wild oat affected the structure of the wheat canopy and how light interception changed throughout the season among both plants.

2.5.2 Below-ground competition

There is a consensus within the literature that root competition is of greater importance than shoot competition with regard to competitive ability (Aspinall, 1960; Snaydon, 1971; Eagles, 1972; Litav and Isti, 1974; Evetts and Burnside, 1975; Walker and King, 2009). Below-ground traits conferring competitive ability include root growth rate, root distribution and size, accumulation rate of resources (Dunbabin, 2007), root density, surface area, rate of resource uptake (Casper and Jackson, 1997), root biomass (Gaudet and Keddy, 1988), root architecture (Schwinning and Ehleringer, 2001; Rubio et al., 2003) and the development of seminal roots (Pavlychenko and Harrington, 1937). Root competition is believed to commence earlier than shoot competition as roots grow more quickly than shoots (Pavlychenko and Harrington, 1937).

Acquiring soil resources in an effective, timely manner is vital for crops competing with weeds (Donald, 1963). In common bean, possessing a shallow root architecture was found to be more successful than deep roots in the uptake of phosphorus (Rubio et al., 2003). Root architecture was also found to be significant for water uptake in that study. A shallow root system is beneficial when rainfall is frequent, as soil moisture will be adequate at shallow depths. By comparison, a deep root system can access deeper soil moisture when rainfall is infrequent (Schwinning and Ehleringer, 2001). The use of root simulation modelling has also demonstrated the importance of traits such as root growth rate and root distribution for rapid the accumulation of resources such as nitrogen, phosphorus, and water (Dunbabin, 2007).

2.6 Crop-weed competition

2.6.1 Factors causing yield loss by weeds

In agriculture, weeds compete with crops for nutrients and cause a crop yield loss or a quality loss. Weed growth factors such as weed density, weed species competitive ability (Pavlychenko and Harrington, 1934), and the size of the weed species, timing of emergence relative to crop (Williams, 1964).

Higher weed densities should reduce crop yields more than lower weed densities. For example, wild oat densities of 60 plants m^{-2} and 160 plants m^{-2} reduced flax yields by 60% and 82%, respectively (Bell and Nalewaja, 1968a). In wheat, wild oat densities of 59 plants m^{-2} and 134 plants m^{-2} reduced yield by 22% and 39%, respectively. Research by Bowden and Friesen (1967) found that only 8 wild oat plants m^{-2} significantly reduced flax yields, whereas 59-84 wild oats m^{-2} were required to reduce yield by the same amount in wheat.

Weed size is another factor that can impact crop yield. Wild oat plants can grow up to 1.5 m in height, while kochia (*Kochia scoparia* L.) can reach 2 m in height; wild mustard is frequently taller than 1.8 m (Royer and Dickinson, 2006a). The height of these weeds plays a factor in their competitive ability. Small weeds such as yellow whitlow grass (*Draba nemerosa* L.), which grows from 3 to 35 cm in height, and pygmyflower (*Androsace septentriolnalis* L.), which extends up to 30 cm in height (Royer and Dickinson, 2006b and Royer and Dickinson, 2006c), will not compete well with any crop at a juvenile stage. However, these weeds will compete with crop seedlings and may cause a yield loss at more mature stages. Weaver (1991) suggested that small weeds may cause insignificant yield losses regardless of growth stages, and because pygmyflower is increasing in number on the prairies (Blackshaw, 2003), there may be an effect of such small weeds as their density increases.

The timing of emergence of weeds relative to the crop is also important, and is probably the most important factor affecting crop-weed competition in western Canada (O'Donovan et al., 1985). For example, Martin and Field (1988) reported that when wheat and wild oats were planted at the same time, wild oat was more competitive, but when wheat was given a three or six week growth advantage on wild oats, wheat was more competitive. In a crop like canola, which has poor initial competitiveness (Melander, 1993; Lemerle et al., 1995), the crop needs to be kept weed-free until the four-leaf stage. Research by O'Donovan et al. (1985) reported that yield loss of wheat and barley increased the emergence of wild oat became earlier relative to the crop. Likewise, Willenborg et al. (2005c) reported that time of emergence and density of wild oats were key to determining the outcome on wild oat – tame oat competition.

2.6.2 Competitiveness of semi-leafless and conventional field pea

Field pea typically lack strong competitive ability due to a short stature, late season canopy closure, slow seedling growth, and small leaf area (semi-leafless) (McVicar et al, 2009). For example Wall et al. (1991) found that 20 plants m^{-2} of wild mustard reduced field pea yield by 2-35%. Vasilakoglou and Dhima (2012) reported that the normal leaf cultivar 'Olympus' reduced wild oat biomass by 16-46% more than the cultivar 'Hardy', which is a semi-leafless cultivar. Both Harker et al. (2008) and Vasilakoglou and Dhima (2012) found that under weed-free conditions, normal leaf cultivars yielded less than semi-leafless cultivars, but they yielded higher under weed competition. Likewise, Harker et al. (2001) reported that weed removal is essential up to two weeks after field pea emergence as competition afterwards will be detrimental to field pea yields. Field pea was subjected to competition from wild oat (*Avena fatua* L.) and redstem filaree (*Erodium cicutarium* L.), which caused a 47 and 31% decline in field pea yield, respectively (Harker et al., 2007). Thus, there is a clear need for more competitive semi-leafless field pea cultivars.

2.6.3 Influence of field pea leaf type on competitive ability

Several studies have shown that there is variation in competitive ability among field pea cultivars (Townley-Smith and Wright, 1994; McDonald et al., 2003 Spies et al., 2011). Wall and

Townley-Smith (1996) reported that some field pea cultivars that exhibited only a minimal yield loss with weed competition were not the highest yielding under weed-free conditions. Cultivars with long vines and quick canopy establishment were the most competitive with weeds. Normal leaf cultivars are known to be highly competitive and exhibit rapid canopy growth. In contrast semi-leafless types are less competitive and grow more slowly (Spies, 2008). While previous studies have compared both normal leaf and semi-leafless cultivars, research has never evaluated competition among semi-leafless cultivars alone. As well, key traits conferring competitiveness have not been identified, yet cultivar selection is the main factor affecting weed population density and the dry weight of weed shoots (Wall and Townley-Smith, 1996). Although there has been no mechanism shown to drive competitive ability in the field pea, leaf area is known to be an important trait of a competitive crop or cultivar (Cote et al., 1992). Unsprayed normal leaf field pea cultivars can yield as much as or more than semi-leafless field pea cultivars that have been sprayed with a herbicide (Harker et al., 2008). The authors also found that in the absence of weed competition, normal leaf cultivars were lower yielding than semi-leafless cultivars; it was only under weed competition that a yield difference was observed (Harker et al., 2008).

2.6.4 Field pea vine length and basal branching influence on competitive ability

Plant height is an important component of crop competitive ability (Harker et al., 2008; Wall et al., 1991). This is also true for field pea. Wall and Townley-Smith (1996) reported that field pea leaf type had little effect on competitive ability and that plant height (vine length) was the most important trait determining the competitive ability of a plant. Vine length is important as it affects how much sunlight a plant will intercept. Normal leaf, tall pea cultivars are able to form a thick canopy of vines that will reduce sunlight penetration to the lower canopy, resulting in higher yields than medium and short cultivars under weed competition (McDonald, 2003). McCue and Minotti (1979) reported that tall and normal leaved field pea cultivars are far superior in preventing weed growth compared with a tall, semi-leafless, or dwarf cultivar. The aforementioned studies demonstrate that if field pea cultivars have elongated vines and a dense crop canopy, then those cultivars should be more competitive with weeds (Wall and Townley-Smith, 1996).

Basal branching (branching in lower nodes) of field pea was also proposed to influence field pea competitive ability (Spies et al., 2011). Basal branching is a function of cultivar and plant density and has been shown to offset poor ground cover under a reduced stand of field pea. (Spies et al., 2010). It has also been shown that basal branching will result in increased light interception and therefore, more photosynthesis (Spies et al., 2010). Spies et al. (2010) found that field pea cultivars with greater basal branching also were able to achieve maximum yield at lower plant densities because they are able to intercept more light compared to cultivars with low basal branching. However, branching did not vary among cultivars and was not linked to competitiveness with weeds (Spies et al., 2011). It is likely that basal branching did not confer competitive ability because little genetic variation existed among the cultivars tested. In addition, other traits could have masked any observable difference between competitive ability and basal branching (Spies et al., 2011).

3.0 Evaluating the ability of semi-leafless field pea cultivars to compete with and withstand competition from weeds

3.1 Introduction

Field pea is a poor competitor with weeds due to slow seedling growth, short stature, and slow canopy closure (Saskatchewan Pulse Growers, 2009). A recent weed survey in Alberta reported that 67% of field pea fields suffered yield losses due to the presence of weeds, compared with only 40% for canola (*Brassica napus* L.) and 27% for barley (*Hordeum vulgare* L.) (Harker, 2001). Competition from volunteer barley (*Hordeum vulgare* L.) resulted in field pea yield losses ranging from 30 to 85% (Blackshaw and Harker, 2003). Excellent weed control is critical to field pea production, but is difficult to achieve (Townley-Smith and Wright, 1994; Harker, 2007). Integrated weed management is one approach that could improve weed control in field pea.

Competitive crop cultivars are a key component of integrated weed management (Dew, 1972). The competitive ability of a crop can be classified either as the ability to tolerate neighbours (competitive response) or the ability to suppress neighbours (competitive effect) (Goldberg and Landa, 1991; Jordan, 1993). Competitive ability can also be classified as the ability to withstand competition (AWC, competitive response) or the ability to compete (AC, competitive effect) (Watson et al., 2006). In studying the competitive ability of cultivars, both aspects need to be considered (Jordan, 1993; Lemerle et al., 1996; Watson et al., 2006) as varietal differences due to weed competition may arise if some cultivars have peak resource demands at times when resource use is low.

Enhancing crop competitive ability is key to weed management (Mohler, 2001; Zerner et al., 2008). Cultivar differences in competitive ability have been identified in various crops including corn (*Zea mays* L.), winter wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), field pea (*Pisum sativum* L.), oat (Av*enua sativa* L.), lentil (*Lens culinaris* L.) and sorghum (*sorghum bicolor* L.) (Staniforth, 1961; Balyan et al., 1991; Richards and Whytock, 1993; Huel and Hucl, 1996; Grevsen, 2003; Wildeman, 2004; Tepe et al., 2005). Above-ground traits such as plant height, vigorous early growth, number of tillers, leaf area, and seed size have been recognized key traits influencing the competitive ability of a crop (Gaudet and Keddy, 1988; Lemerle et al., 1996; Froud-Williams, 1997; Dingkuhn et al., 1999; Willenborg et al., 2005a). However, several below-ground traits can also influence competitive ability, including seminal root development, root biomass, root architecture, and root size (Pavlychenko and Harrington, 1974; Gaudet and Keddy, 1988; Rubio et al., 2003; Dunbabin, 2007).

Typically, crop species differ substantially in their ability to compete for resources (Loomis and Connor, 1995) and in many cases, there is also variation in competitive ability among cultivars of a crop species (Tepe et al., 2005; Willenborg et al., 2005b; Watson et al., 2006). This may not be the case for field pea, however. While current breeding initiatives have substantially improved lodging resistance and ease of harvest, competitive ability may have declined as a result. For example, semi-leafless field pea cultivars are preferentially grown over normal leaf field pea cultivars due to improved lodging resistance and more preferable agronomic traits, but semi-leafless field pea cultivars are less competitive with weeds (Semere and Froud-Williams, 2001; Harker et al., 2008). Leaf area is a key component of a competitive crop stand because of light capture (Loomis and Conner, 1995; Radosevich et al., 2007). Previous research validates this as Harker et al. (2008) noted that unsprayed, normal leaved cultivars of field pea yielded similar to or more than semi-leafless cultivars that received a herbicide application. Likewise, normal leaf pea cultivars were more competitive with wild mustard than were semi-leafless pea cultivars (Wall et al., 1991). In lentil, Tepe et al. (2005) reported that cultivars also differed significantly in their ability to compete with weeds, although the contribution of varietal effects to weed suppression was modest.

Current breeding efforts in some pea market classes are focused on breeding for smaller seed size to reduce seed costs, despite the importance of seed size in suppressing weed interference (Xue and Stougaard, 2002; Willenborg et al., 2005a). Consequently, it is possible that the competitive ability of field pea may have been depressed concomitantly as small seed size has been selected for. It is also possible that the variation for traits that confer competitive ability may be negligible between cultivars due to the close genetic similarity between cultivars. It is important, therefore, to understand if differences in competitive ability exist among field pea cultivars and if so, which traits are driving these differences.

Little published information exists regarding competitive differences among semi-leafless field pea cultivars, and even less information has been published regarding the specific traits that determine competitiveness against weeds. Since screening cultivars is often a prelude to searching for traits contributing to competitive ability, the primary objective of this study was to determine if competitive differences exist among semi-leafless field pea cultivars. The secondary objective was to identify which above-ground traits correlated with increased competitive ability among cultivars.

3.2 Materials and Methods

3.2.1 Experimental design and location

Field experiments were conducted in 2012 and 2013 at three locations: the Kernen Crop Research Farm (KCRF) (52° 9' N and 106° 32' W) near Saskatoon, the Goodale Research Farm (GRF) (52° 02' N and 106° 34' W) near Saskatoon, and the St. Albert Research Station (SARS) (53° 41' N and 113° 37' W) near St. Albert, AB. The Kernen site was lost to excess moisture in 2012 and will not be discussed further. The KCRF and GRF sites were located on a Dark Brown Chernozemic clay soil with a pH of 6.5 to 7.4, while the SARS site was located on an Orthic Black Chernozemic clay loam soil with a pH of 7.4 (Table 3.1).

Table 3.1 Soil test results at Goodale and Kernen sites in Saskatchewan, and St. Albert, AB in 2012 and 2013.

	Goodale		Kernen		St. Albert	
Soil properties	2012	2013	2012	2013	2012	2013
	0-15 cm	0-15 cm	0-15 cm	0-15 cm	0-15 cm	0-15 cm
pH	6.6	6.4	7.3	7.4	6.6	7.8
Nitrate (lb ac^{-1})	9	19	15	46	26	66
Phosphorous (lb ac^{-1})	46	>60	>60	42	106	80
Potassium (lb ac^{-1})	>600	585	>600	>600	493	533
Sulfur (lb ac^{-1})	27	>48	16	16	28	43
Organic matter (%)	2.8	2.6	3.6	3.8	10.7	10.0

All plots were established on wheat or barley stubble. The experiment was conducted as a split-block randomized complete block design with four replicates per treatment. Treatments consisted of fourteen semi-leafless field pea cultivars (sub plots) representing four market classes (green, yellow, dun, forage) and a no-crop control grown either in the presence or absence of weeds (main plots, Clearfield® wheat and canola, hereafter referred to as model weeds). Field pea cultivars were chosen based on vine length and seed size, providing variation in traits that could be important to competitive ability (Table 3.2). This resulted in 30 experimental units (treatments) in each replicate, with a sub-plot (field pea cultivar) size of 2 x 7 m.

3.2.2 Experimental procedures

Seed for field pea cultivars was obtained from pedigreed seed growers, while BASF provided certified seed for the model weeds (spring wheat and canola). The weedy half of each block was planted with the spring wheat cultivar 'CDC Imagine' and the canola cultivar '45H73' at target densities ranging between 20 and 25 plants m^{-2} for each species. Seeding rates were adjusted based on germination tests and an assumed mortality of 20% for wheat and 50% for canola. The model weed species are tolerant to imidazolinone herbicides, which allowed for the removal of all weeds, except the model weeds, thus providing relatively consistent densities with which to assess competitive differences among cultivars. Prior to planting, the field pea seed was treated with Vitaflo 280® seed treatment (15.59% carbathiin and 13.25% thiram) at a rate of 300 ml 100 kg^{-1} of seed.

Table 3.2 Cultivars and their classification based on vine length and seed size. From the Alberta Seed Guide (2010) and Saskatchewan Seed Guide (2012).

Cultivar	Market Cass	Vine Length	Classification	Seed Size	Classification
		cm		g/1000	
CDC Mozart	yellow	61	Short	241	Large
CDC Meadow	yellow	76	Tall	221	Medium
Cutlass	yellow	68	Medium	233	Medium
Reward	yellow	76	Tall	248	Large
SW Midas	yellow	66	Medium	213	Small
CDC Centennial	yellow	61	Short	259	Large
CDC Patrick	green	79	Tall	201	Small
Camry	green	57	Short	258	Large
Cooper	green	71	Medium	280	Large
CDC Sage	green	71	Medium	199	Small
CDC Striker	green	66	Medium	244	Medium
Stratus	green	55	Short	260	Large
CDC Dakota	dun	85	Tall	205	Small
CDC Leroy	forage	95	Tall	150	Small

Field operations were carried out as outlined in Table 3.3. The plot area at all sites received an application of 900 g ae ha^{-1} of glyphosate prior to seeding or immediately after planting to control emerged weeds. Sites in Saskatchewan were seeded with a cone seeder using disk openers with a row spacing of 23 cm. The two sites in Alberta were sown with a small plot cone seeder with atom jet openers on 20 cm row spacing. Field peas were planted at a depth of 5 cm at all sites, at a target plant density of 75 plants m^{-2}. The soil was inoculated with granular *Rhizobium leguminosarum* at 4.6 kg ha^{-1}. Monoammonium phosphate (11-52-0-0) was placed with the seed at planting at a rate (actual) of 3 kg ha^{-1} of nitrogen and 12 kg ha^{-1} of phosphorus. After sowing the field peas, model weeds were planted at a depth of 2 cm by cross seeding them over the appropriate main plot. Odyssey® (35% imazamox + 35% imazethapyr) was applied at a rate of 43 g ai ha^{-1} across the entire trial at the 4 to 6 node stage of crop growth. Any weeds remaining after the in-crop herbicide application were removed by hand.

In 2012, plots at GRF received an application of prothioconazole at a rate of 175 g a.i. ha^{-1} to control *Mycosphaerella pinodes*. A second fungicide application was made three weeks later with chlorothalonil at a rate of 1500 g a.i. ha^{-1}. In 2013, both the GRF and KCRF received an application of prothioconazole at a rate of 150 g a.i. ha^{-1}, while the SARS site received an application of chlorothalonil at a rate of 1000 g a.i. ha^{-1}. All application timings corresponded to the early and late flowering stages of field pea. In 2012, lambda-cyhalothrin was applied at 10 g a.i. ha^{-1} rate at the early pod crop stage to control aphids (*Aphidoidea*).

Crop and model weed days to emergence were recorded when approximately 50% of the seedlings had emerged. Field pea crop density was recorded at the five- to six- node stage by counting the number of plants in two random, 1 m rows. Model weed densities were recorded in three random, 0.25m^2 quadrats. At the three Saskatchewan sites, photosynthetically active radiation (PAR) was assessed by placing a ceptometer above the crop canopy and at the mid and base of the crop canopy in two locations per plot. The number of days to full canopy closure was then determined by assessing when light interception (PAR) measurements remained constant.

Table 3.3 Management of field trials at Goodale and Kernen sites in Saskatchewan and St. Albert, AB in 2012 and 2013.

	Goodale	**St. Albert**	**Goodale**	**Kernen**	**St. Albert**
	(2012)		**(2013)**		
Seeding Date	June 1	May 17	May 15	May 15	May 22
Pre-seed/pre-emergence herbicide Glyphosate (900 g a.e. ha^{-1})	June 4	May 15	May 16	May 16	May 20
In-crop herbicide Imazamox and Imazethapyr (43 g a.i. ha^{-1})	June 30	June 22	June 7	June 7	June 21
1st Fungicide application	July 6 Prothioconazole 174 g a.i. ha^{-1}	July 11 Chlorothalonil 1 kg ha^{-1}	July 4 Prothioconazole 151 g a.i. ha^{-1}	July 4 Prothioconazole 151 g a.i. ha^{-1}	July 9 Chlorothalonil 1 kg ha^{-1}
2nd Fungicide application	July 26 Chlorothalonil 1.5 kg ha^{-1}	NA	NA	NA	July 23 Chlorothalonil 1 kg ha^{-1}
Insecticide (Lambda-cyhalothrin) 10 g ai ha^{-1}	Aug. 9	NA	NA	NA	NA
Desiccation (Diquat) 420 g ai ha^{-1}	Sept. 6	NA	Aug. 22	Aug. 22	NA
Harvest	Sept. 10	Sept. 5	Aug.28	Aug. 28	Sept. 14

Vine length was measured on five randomly selected plants in each plot at the flowering stage by taking the height from the soil surface to the top of the apical meristem. Leaf area index (LAI) of the various pea cultivars was determined at flowering by selecting plants in one, $0.125m^{-2}$ area and removing the leaves from these plants. Leaves were then scanned by a leaf area meter and the LAI was determined. In 2013, the petioles and tendrils were also included in this measurement. Field pea and model weed aboveground biomass was determined by cutting all above-ground plant material at the soil surface from two, 0.25m^{-2} areas in each plot. The crop and model weeds were then separated, placed in individual paper bags, dried at 80°C for 72 hours and weighed. Lodging was determined just before harvest by assessing the percent crop lodging in each plot.

All Saskatchewan sites were desiccated with diquat at a 420 g a.i. ha^{-1} rate at harvest maturity (bottom of the pea plants were ripe and seeds detached in the pod). Plots were harvested at the SARS site by using hand sickles to cut a 1.83 m x 4 row area (1.5m^{-2}) in each plot. Samples were placed into cloth bags, dried in a large drying oven at 80°C for 96 hours and threshed in a stationary threshing machine. In 2012 the SARS site received hail damage and consequently, a 0.25 m^{-2} from each plot was vacuumed from the soil surface and weighed to account for any potential harvest losses. Plots at the Saskatchewan sites were harvested with a small plot combine that cut a 6.58 m^{-2} area from each plot. Seed at all sites was dried to a constant moisture of 16%, weighed, and cleaned with a dockage tester to obtain a clean yield and also, to separate the model weed seed from the harvested field pea samples. A thousand seed weight (TSW) was obtained for each plot by counting 250 seeds, weighing them and multiplying by a factor of four.

Ability to withstand competition (AWC) measures the tolerance to weed interference, while ability to compete (AC) is the ability to reduce weed seed production (Watson et al., 2006). AWC was calculated as:

$$AWC = 100(Y_{wp}/Y_{wfp})$$

where Y_{wp} is the field pea yield from the weedy plot and Y_{wfp} is the field pea yield from the weed-free plots. Ability to Compete (AC) was calculated as:

$$AC = 100 - \%dockage$$

where percent dockage is calculated as the amount of model weed seed in each harvested sample (Watson et al., 2006).

3.2.3 Statistical Analysis

Residuals initially were tested to ensure that the assumptions of ANOVA were met. PROC UNIVARAITE was used to assess normality and Levene's test was used to test for homogeneity of error variances. Where residuals did not conform to the assumptions of ANOVA, data were square root or log transformed. Log_{10} transformations were performed on petiole and tendril area at SK sites and field pea density at AB sites. All transformed data were back transformed prior to presentation.

Analysis of Variance (ANOVA) was performed using the mixed model procedure of SAS (SAS Institute, 2011). All data were analyzed without the no-crop control as its purpose was to provide baseline information only and its inclusion makes detecting true differences between cultivars more arduous. Field pea cultivars and the competition treatment (presence/absence of weeds) were considered fixed effects in the statistical model, while random effects consisted of block nested within site-year, site-year, and the combinations of site-year by fixed effects interactions. The random effects were examined using the COVTEST option of PROC MIXED to determine if the site-years could be combined. Due to significant site-year by treatment interactions between site-years within the same province, data were pooled across years but combined within each province. Thus, Saskatchewan (SK) encompasses all 3 years in Saskatchewan and Alberta (AB) includes the two years of data in Alberta. Means separation was performed using Tukey's HSD at $P < 0.05$. Correlations were performed using the Spearman method of PROC CORR to assess the relationship between above-ground traits that may confer competitive ability. Single degree of freedom contrasts were calculated using ESTIMATE statements in SAS to compare means among green and yellow semi-leafless field pea cultivars.

Analysis of Covariance (ANCOVA) was also conducted to assess whether field pea density and emergence should be used as covariates. ANCOVA and ANOVA gave the same p-values, cultivar ranking, conclusions and interpretation. Moreover, regressions and correlations performed on field pea density/emergence and the response variables showed no relationship between density and any of the variables of interest. Thus, pea density and emergence were not considered significant covariates in any of the variables measured in this study (data not shown).

3.3 Results

3.3.1 Climate data

Climate varied greatly among the site-years, and 2012 proved to be a difficult growing season due to abnormally high rainfall. In 2013, less rainfall provided better growing conditions. Average temperatures in both 2012 and 2013 at all sites were similar to the 30-year averages (Table 3.4).

3.3.2 Crop and model weed emergence

Crop emergence exhibited a significant site-year by cultivar interaction ($P < 0.01$) at SK (Table 3.5), but had no effect on treatment order, and treatments did not differ among site-years;

thus data were combined across years within each province. Field pea emergence did not differ among cultivars or competition treatments, nor was there a cultivar by competition treatment interaction ($P > 0.05$) at AB (Table 3.6). At the SK sites, however, emergence among cultivars differed significantly ($P < 0.01$). Reward and Stratus exhibited significantly slower emergence, emerging between 12-13 d after seeding while most of the other cultivars emerged 10-11 d after seeding (Figure 3.1). Competition treatments and the competition treatment by cultivar interaction did not differ ($P > 0.05$) at SK. At all sites, model weed emergence was not significantly different ($P > 0.05$) between treatments, suggesting model weed emergence was consistent throughout the trial.

Table 3.4 Monthly rainfall (mm) and the mean daily temperature (C) for Goodale and Kernen sites in SK and St. Albert, AB. Data are from May to September in 2012 and 2013, as well as the long term (30-yr) average (normal).

		Rainfall			Temperature		
Location	Month	2012	2013	Normal ¥	2012	2013	Normal ¥
		(mm)			(°C)		
Kernen	May	150.1	19.4	34.4	10.2	12.3	11.8
	June	113	123.0	63.6	15.8	15.6	16.1
	July	90.6	40.2	53.8	19.7	17.7	19.0
	August	66	13.8	44.4	17.3	18.6	18.2
	September	21.2	16.6	36.8	12.8	15.3	12.0
	Total	440.9	213	233	-	-	-
Goodale	May	143	11	34.4	10.7	13.2	11.8
	June	97.6	121.2	63.6	15.6	15.9	16.1
	July	83.4	40.5	53.8	19.1	17.8	19.0
	August	66.1	14	44.4	17.8	18.7	18.2
	September	23.4	19.8	36.8	13.3	15.9	12.0
	Total	413.5	206.5	233	-	-	-
St. Albert	May	44.0	39.5	42.9	10.5	14.2	10.2
	June	44.7	86.7	72.7	15.2	15.5	14.1
	July	216.1	76.8	95.6	18.6	17.1	16.2
	August	49.6	53.6	54.9	17.4	18.2	15.2
	September	35.4	10.8	40.3	13.6	14.4	10.2
	Total	389.8	267.4	306.4	-	-	-

¥ 1970 – 2000 Canadian Climate normals obtained from Environment Canada (2014).

Table 3.5 *P*-values for crop emergence (CEMER), weed emergence (WEMER), crop density (CDEN), weed density (WDEN), vine length (VL), days to full crop canopy closure base canopy (DFCCB), leaf area index (LAI), petiole and tendril area (PTA), weed biomass (WBM), crop biomass (CBM), lodging (LODG), weed seed production (WYLD), and crop yield (CYLD) of three station-years at Goodale and Kernen sites in Saskatchewan in 2012 and 2013.

Source	CEMER	WEMER	CDEN	WDEN	VL	DFCCB	LAI	PTA	WBM	CBM	LODG	WYLD	CYLD
Cultivar (CU)	0.004**	0.105	0.006**	0.565	< 0.001***	0.199	0.022*	0.034*	0.173	0.001**	<0.001***	0.029*	0.001***
Competition (CO)	0.983	NA	0.226	NA	0.965	0.967	0.247	0.096	NA	0.020*	0.303	NA	0.071
CU X CO	0.999	NA	0.279	NA	0.613	0.533	0.685	0.917	NA	0.663	0.001***	NA	0.090
Site-year (SY)	0.165	0.188	0.371	0.444	0.246	0.431	0.216	0.369	0.309	0.199	0.196	0.365	0.278
Rep	0.028*	0.133	0.038*	0.061	0.048*	0.015*	0.088	0.288	0.203	0.064	0.249	0.178	0.038*
Rep X CO	0.215	NA	0.245	NA	0.145	0.152	0.226	0.241	NA	0.196	0.299	NA	0.249
SY X CU	0.001***	0.206	0.098	0.495	0.015*	0.327	0.075	0.441	0.232	0.451	0.012*	0.451	0.061
SY X CO	0.082	NA	0.242	NA	0.100	0.335	0.126	0.259	NA	0.223	0.349	NA	0.149
SY X CO X CU	0.190	NA	0.306	NA	0.222	0.299	0.323	0.222	NA	0.216	0.564	NA	0.235

*, **,*** , significant at the 0.05, 0.01, and 0.001 probability levels. NA denotes not applicable.

Table 3.6 P-values for crop emergence (CEMER), weed emergence (WEMER), crop density (CDEN), weed density (WDEN), vine length (VL), leaf area index, petiole and tendril area (PTA), weed biomass (WBM), crop biomass (CBM), lodging (LODG), weed seed production (WYLD), and crop yield (CYLD) of two-station years at St. Albert, AB in 2012 and 2013.

Source	CEMER	WEMER	CDEN	WDEN	VL	LAI	PTA	WBM	CBM	LODG	WYLD	CYLD
Cultivar (CU)	0.116	0.100	0.036*	0.941	< 0.001***	0.977	0.149	0.279	0.125	0.001**	0.277	0.154
Competition (CO)	0.917	NA	0.749	NA	0.862	0.146	0.199	NA	0.561	0.166	NA	0.241
CU X CO	0.689	NA	0.783	NA	0.968	0.745	0.857	NA	0.116	0.271	NA	0.177
Site-year (SY)	0.232	NA	0.431	0.511	0.361	0.234	NA	0.369	0.401	0.487	0.372	0.227
Rep	0.122	0.999	0.297	0.320	0.075	0.046*	0.176	0.272	0.289	0.235	0.136	0.082
Rep X CO	0.357	NA	0.353	NA	0.088	0.152	0.078	NA	0.359	0.432	NA	0.108
SY X CU	0.028*	NA	0.094	0.366	0.096	0.060	NA	0.241	0.424	0.471	0.068	0.301
SY X CO	0.197	NA	0.161	0.240	0.167	0.195	NA	NA	0.163	0.415	NA	0.163
SY X CO X CU	0.281	NA	0.339	NA	0.152	0.237	NA	NA	0.209	0.618	NA	0.316

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels. NA denotes not applicable.

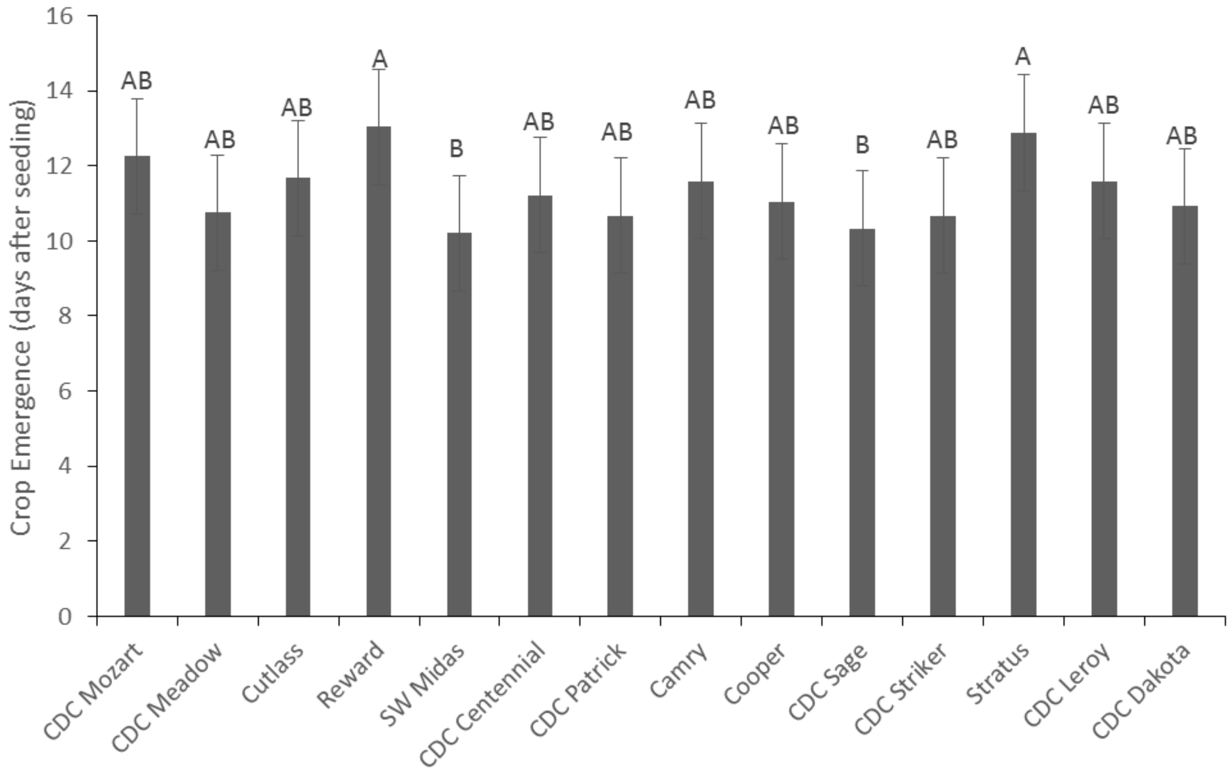


Figure 3.1 Emergence of cultivars at the Saskatchewan sites in 2012 and 2013. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference based on $HSD_{0.05}$.

3.3.3 Crop and model weed density

Field pea densities differed significantly between cultivars at both SK and AB. At the AB sites, Reward had significantly lower pea densities than SW Midas and CDC Leroy; average densities for these cultivars were 60, 86, and 86 plants m^{-2}, respectively (Figure 3.2). All other cultivars exhibited no differences at the AB sites. Similarly, Reward and Stratus had significantly lower densities than the other cultivars at the SK sites (59 and 58 plants m^{-2}, respectively) (Figure 3.2). These densities are significantly lower than the recommended planting density of 75 plants m^{-2} (Alberta Agriculture and Rural Development, 2007). Both competition and the competition by cultivar interaction did not affect crop density, nor did model weed density ($P > 0.05$) (Tables 3.5 and 3.6).

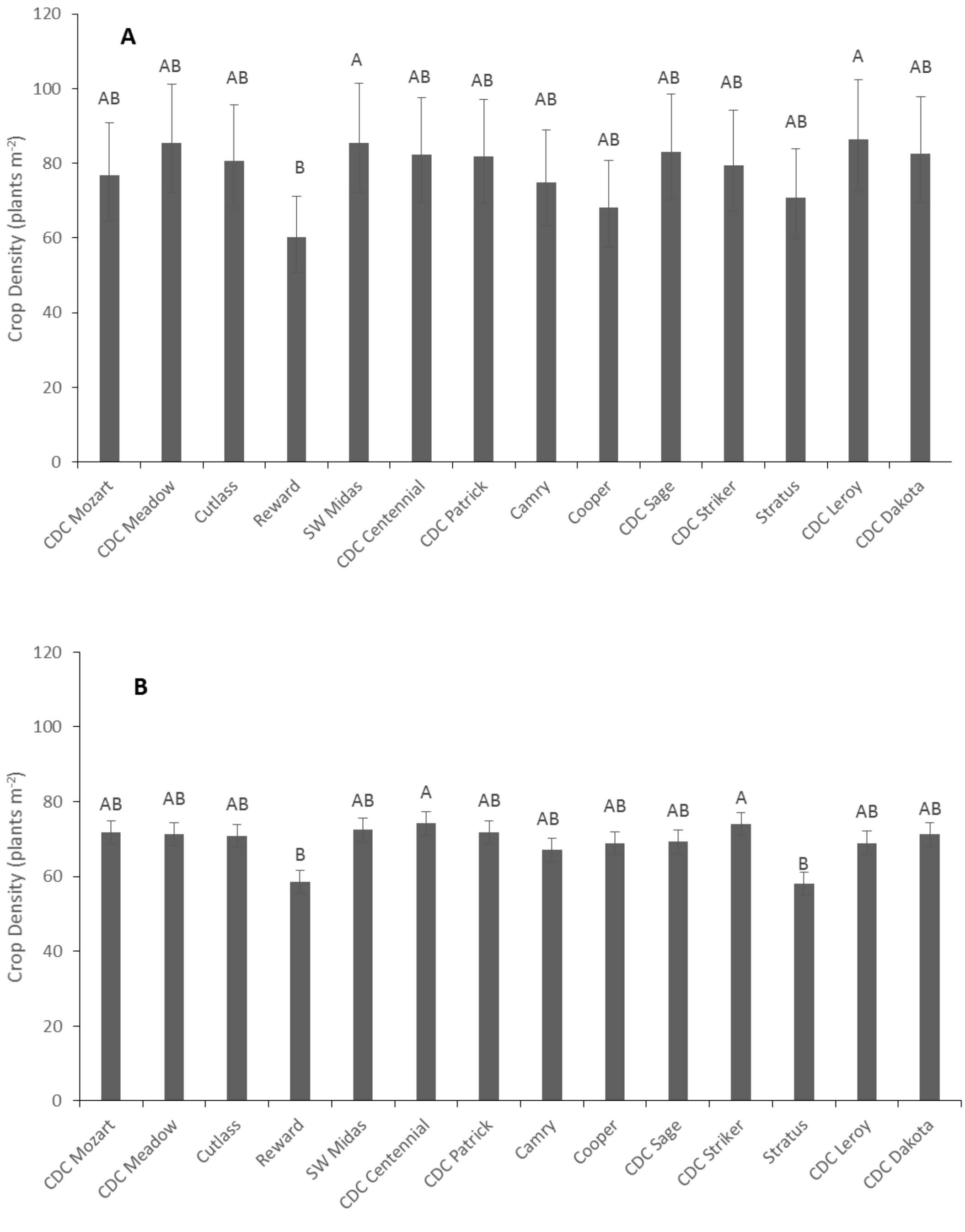


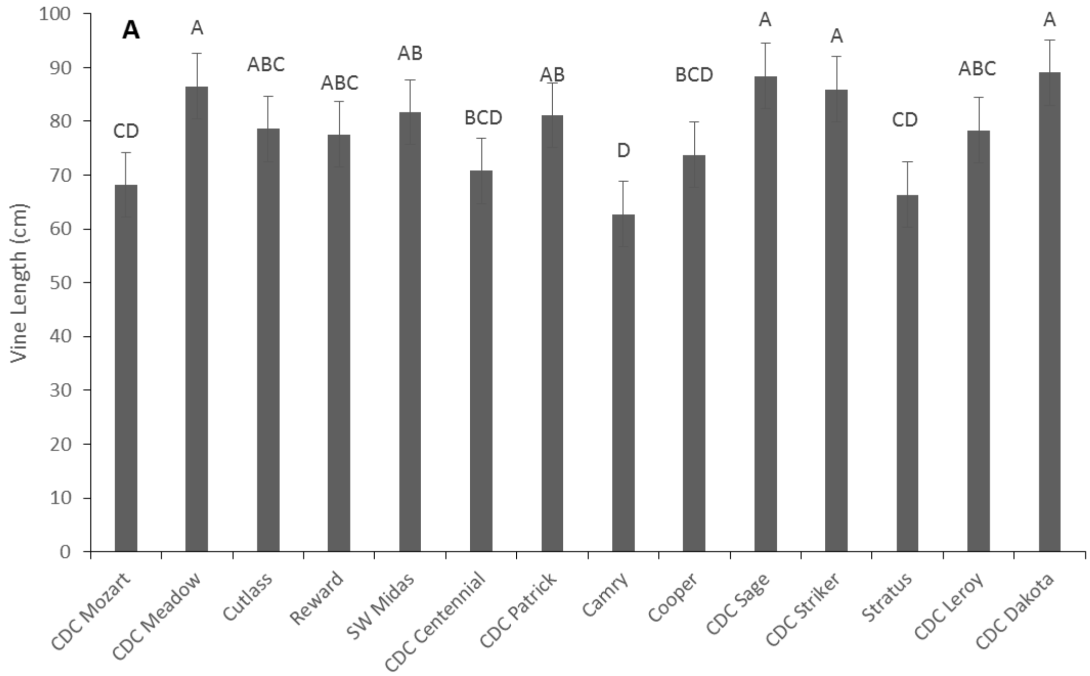
Figure 3.2 Crop density of cultivars at the Alberta sites (A) and Saskatchewan sites (B) in 2012 and 2013. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference based on $HSD_{0.05}$.

3.3.4 Vine length

Cultivars exhibited significant differences ($P < 0.001$) in their vine lengths at both SK and AB ($P < 0.001$) (Figure 3.3). CDC Dakota, CDC Patrick, CDC Meadow, and CDC Sage had longer vine lengths than CDC Mozart, Stratus and Camry at SK (Figure 3.3). A 48% difference in vine length was observed between CDC Dakota and Camry, the longest and shortest cultivars, respectively. Similar results were noted at the AB sites, where CDC Dakota, CDC Sage, CDC Meadow, CDC Striker, SW Midas, and CDC Patrick exhibited longer vine lengths than, CDC Mozart, Stratus, and Camry (Figure 3.3). The difference between the cultivar with the longest and shortest vine length (CDC Dakota and Camry) was only 41% at this site. Vine length was not affected by model weed competition, nor was the interaction between competition and vine length significant in any of the site-years.

3.3.5 Light interception traits

Leaf area index (LAI) was significantly different among cultivars at the SK ($P < 0.05$) sites but not the AB sites. At SK, Reward, and Camry produced a statistically lower LAI compared to CDC Striker (Figure 3.4). The difference between the cultivar with the largest LAI (CDC Striker) and least LAI (Camry) was 38% at SK. The main effect of competition and the interaction between competition and cultivar were not significant in any of the site-years.



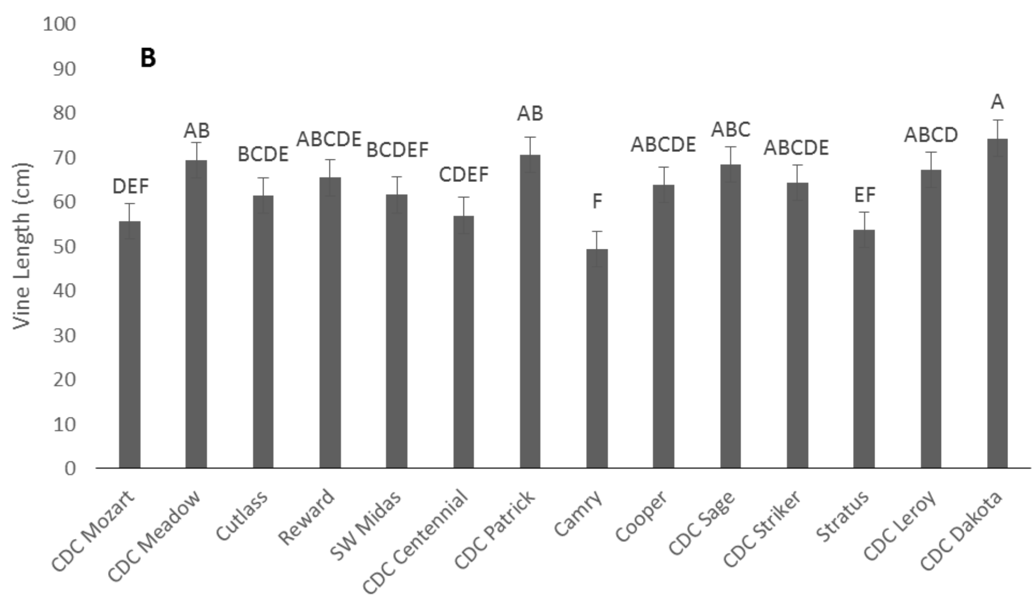


Figure 3.3 Vine length of cultivars at the Alberta sites (A) and the Saskatchewan sites (B) in 2012 and 2013. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference based on $HSD_{0.05}$.

Days to full canopy closure base crop canopy (DFCCB) were not statistically ($P > 0.05$) different among cultivars or competition treatments in any of the site-years (Tables 3.5 and 3.6). Likewise, no significant differences existed in petiole and tendril area (PTA) among competition treatments. However, significant differences were observed between cultivars at the SK site for petiole and tendril leaf area. At this site, the difference between cultivars for petiole and tendril area was substantial, with 58% greater leaf area for CDC Dakota compared to Stratus (797 cm^2), the highest and lowest PTA cultivars, respectively. No differences were observed at the AB sites for any of the main effects or interactions

3.3.6 Crop biomass

Field pea biomass was significantly reduced (37%) in the presence of weeds at SK (Table 3.5), although no significant effect of weed competition was detected at AB (Table 3.6). CDC Striker was very competitive at the SK sites and produced significantly more biomass than all other cultivars except CDC Dakota, CDC Sage, CDC Centennial, SW Midas, CDC Meadow, CDC Patrick, and CDC Mozart (Figure 3.5). Collectively, these eight cultivars produced more biomass than most of the other cultivars, regardless of the weed competition (no interaction between competition and cultivar). The high biomass production observed for CDC Striker may be due, in part, to a very high LAI (Figure 3.4). There were no significant differences among cultivars for biomass production at AB ($P > 0.05$). Likewise, neither the cultivar by competition interaction nor the main effects or interactions for model weed biomass production were significant for any of the site-years (Tables 3.5 and 3.6).

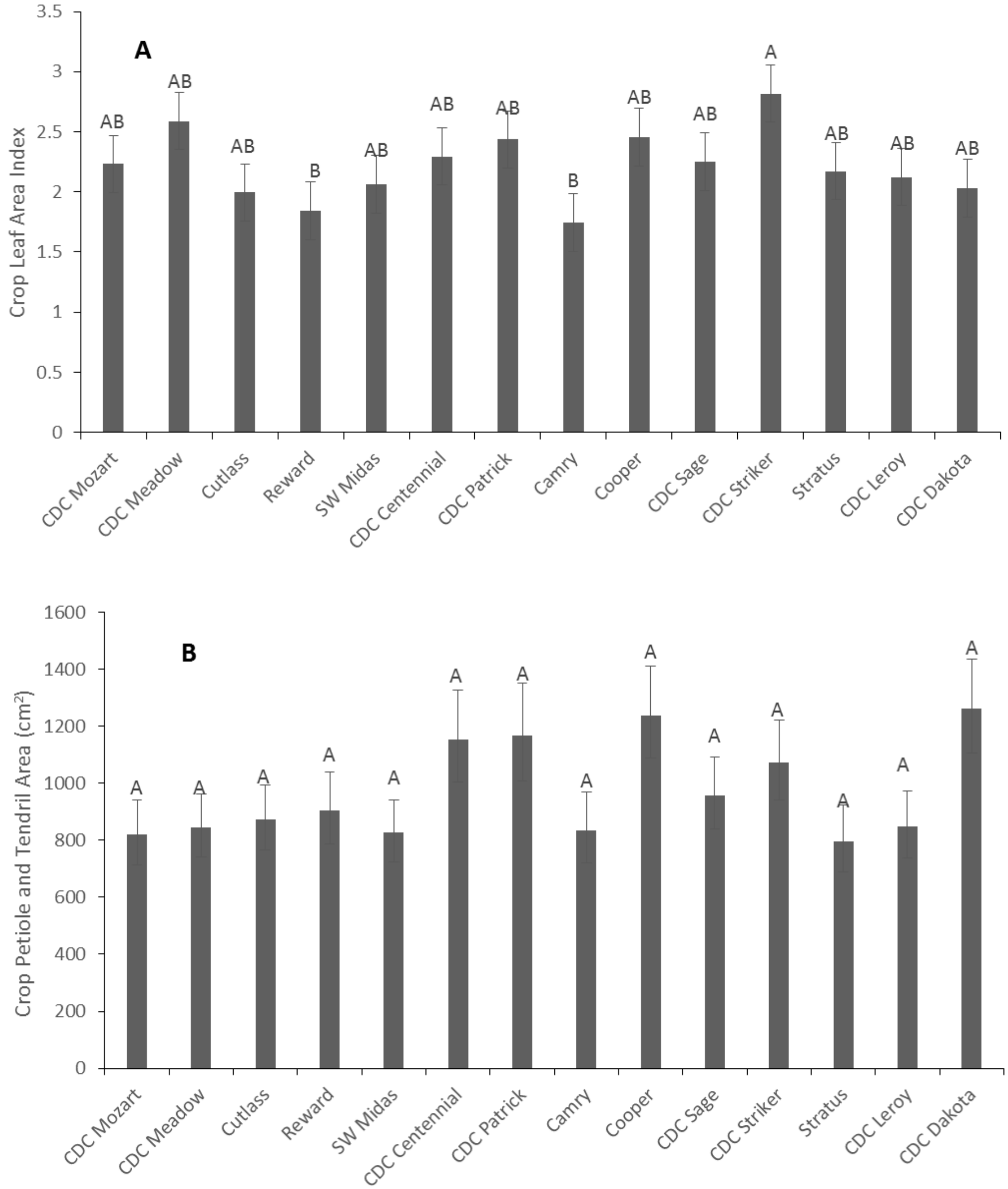


Figure 3.4 Effect of competition for light on: (A) Leaf area index and (B) Petiole and tendril area at Goodale and Kernen in 2012 and 2013. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference based on $HSD_{0.05}$.

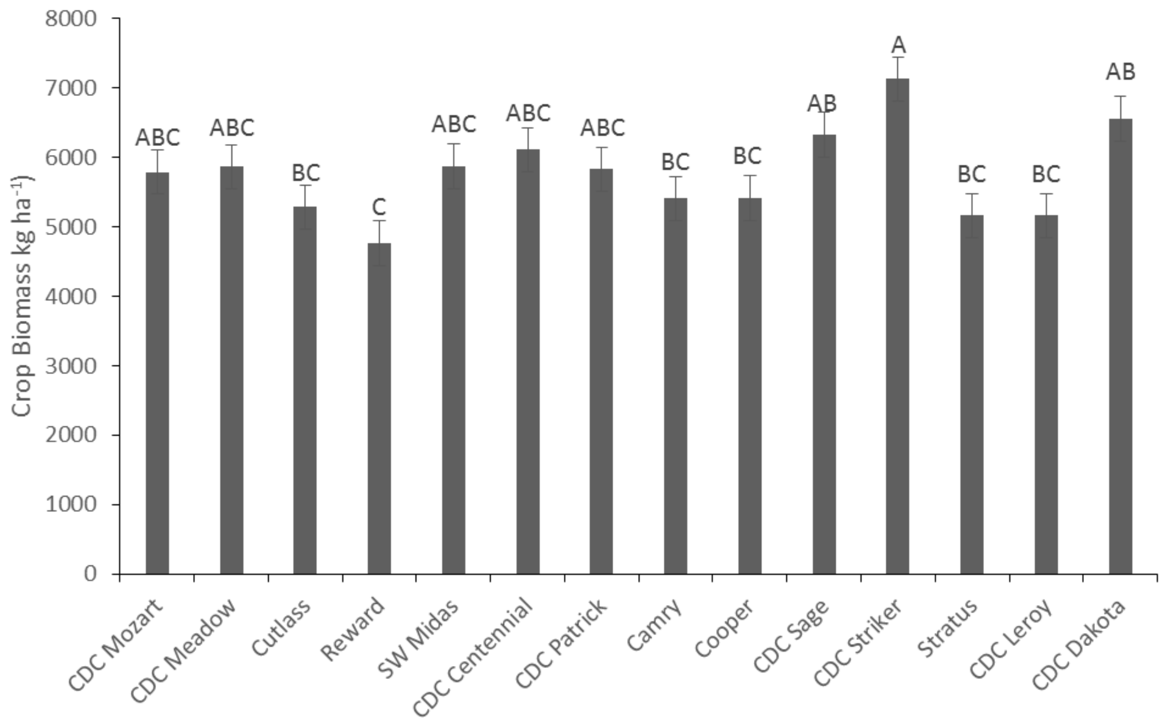


Figure 3.5 Effect of field pea cultivar on crop biomass at Goodale and Kernen in 2012 and 2013. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference based on $HSD_{0.05.}$

3.3.7 Crop lodging

Cultivars exhibited significant differences in crop lodging at AB and at SK (Figures 3.6 and 3.7). Due to a cultivar by competition interaction at SK, data were analyzed within competition treatments. CDC Leroy, Camry, and Cutlass were significantly more lodged than the majority of the other cultivars at AB (Figure 3.6). A 28-fold reduction in lodging was observed between CDC Leroy and CDC Dakota. In the weedy plots at SK sites CDC Mozart and CDC Centennial were more significantly lodged than all of the other cultivars, with a 22-fold reduction observed between the most (CDC Mozart) and least (SW Midas) lodged cultivar (Figure 3.7). Similar results were observed in the weedy plots at the SK sites.

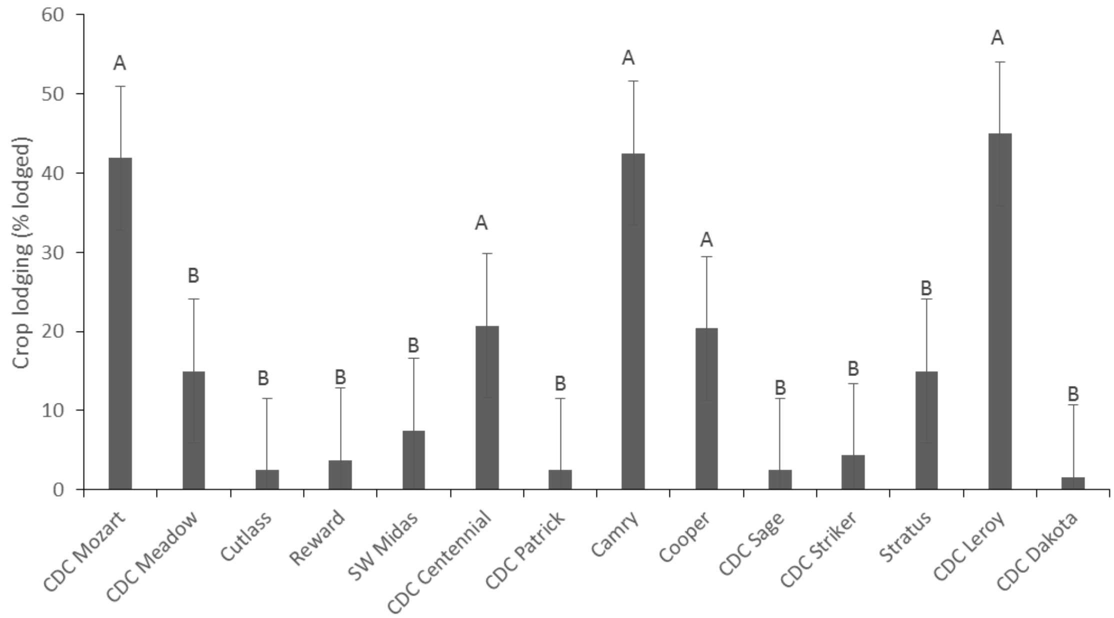


Figure 3.6 Lodging of cultivars at St. Albert in 2012 and 2013. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference based on $HSD_{0.05}$.

3.3.8 Crop yield

At SK sites in 2011 and 2012, a significant difference in field pea yield was observed ($P < 0.001$) between cultivars (Table 3.5). CDC Dakota, CDC Patrick, CDC Meadow, CDC Leroy, and Cooper were the highest yielding cultivars and yielded significantly more than Stratus and Reward (Figure 3.8). Regardless of the presence of weeds (no significant effect of competition or the main effects interaction), large yield differences were observed as CDC Dakota (4598 kg ha^{-1}) produced 48% more seed yield than Reward (3107 kg ha^{-1}), the highest and lowest yielding cultivars, respectively. Interestingly, CDC Dakota, which had a low LAI compared to other cultivars, was the highest yielding cultivar at the SK sites in both years. A significant cultivar by model weed interaction did not exist ($P = 0.09$) in any site-year, which indicates that field pea cultivars did not yield differently in the presence or absence of weed competition. No significant differences in crop yield were observed between either the main effects (cultivar and weed competition) or the interaction between the two at the AB sites.

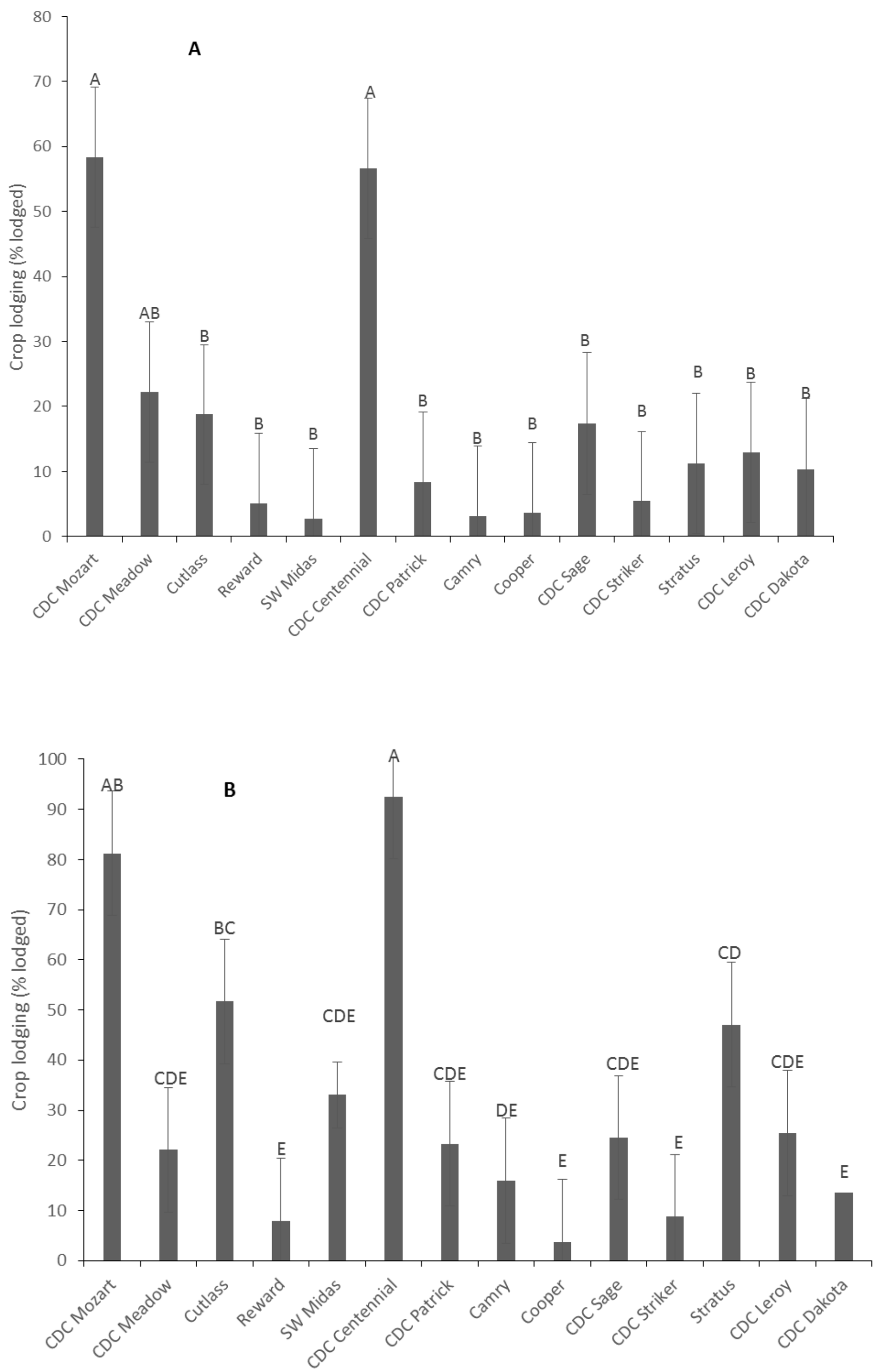


Figure 3.7 Lodging of cultivars in weedy plots (A) and weed-free plots (B) at Goodale and Kernen in 2012 and 2013. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference based on $HSD_{0.05.}$

3.3.9 Model weed seed production

Model weed seed production was not different among cultivars at AB, but was significantly different between cultivars at SK (Tables 3.6 and 3.5). Weed seed production varied greatly among cultivars; a 70% increase in weed seed production was observed for Reward (1196 kg ha^{-1}) compared with CDC Dakota (700 kg ha^{-1}) (Figure 3.8). The greatest model weed production was observed in Stratus and Reward, while the remaining cultivars had significantly lower weed seed production. No significant differences were observed for the main effects of competition or the interaction between competition and cultivar at the SK sites (Table 3.5). Likewise, cultivar, competition, and their interaction had no significant impact on model weed seed production at any of the AB sites.

3.3.10 Competitive ability of semi-leafless field pea cultivars

3.3.10.1 Ability to withstand competition (AWC) and ability to compete (AC)

Ability to withstand competition (AWC) differed significantly among cultivars at SK but not at AB (Table 3.7). CDC Centennial, CDC Mozart, CDC Patrick, CDC Sage, and CDC Striker exhibited significantly greater AWC values than most of the other cultivars. This indicates that they were better able to withstand the presence of competitors than were other cultivars (Table 3.8). Values for AWC ranged from 91 to 62 and represented a yield loss that ranged from 9% to 38%. The range in AWC values represents a 1.5-fold decrease separating the most able from the least able cultivar to withstand competition.

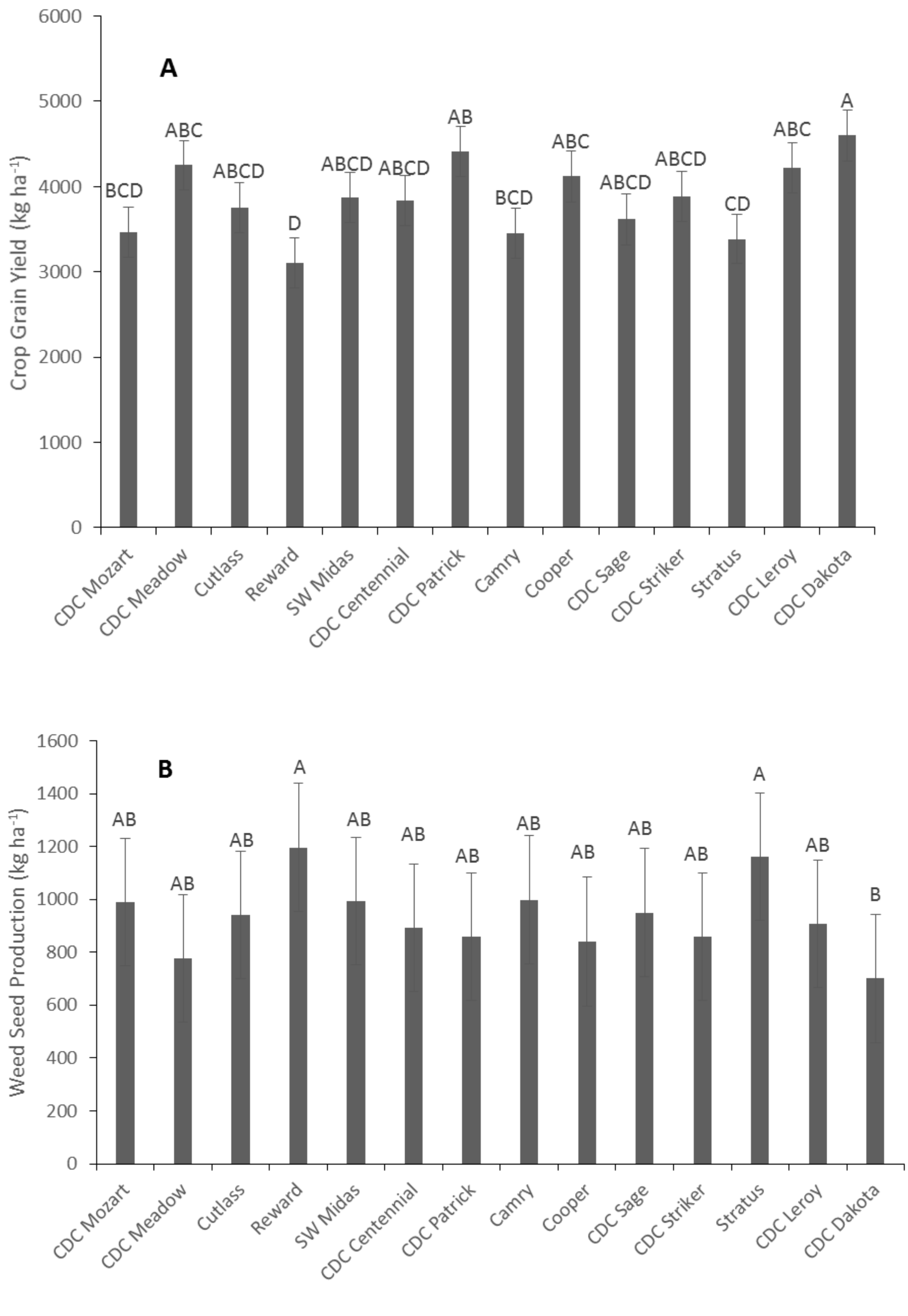


Figure 3.8 Effect of field pea cultivar on: (A) Crop grain yield and (B) Model weed seed production at two sites in Saskatchewan in 2012 and 2013. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference based on $HSD_{0.05}$.

Ability to compete measures weed suppressive ability of the cultivars, commonly referred to as the competitive effect. Significant differences in AC were only detected among cultivars at SK (Table 3.7). CDC Dakota, CDC Patrick, and CDC Meadow were the strongest at suppressing model weeds, while Camry, Stratus, and Reward were poorest; the remaining eight cultivars were intermediate to these (Table 3.8). AC values ranged from 86 to 69 (14 to 31% seed return) for CDC Dakota and Reward, respectively, which indicates that CDC Dakota was 25% more weed suppressive than Reward. Reward was clearly the least competitive of the cultivars studied, exhibiting the lowest AWC and AC values at SK across all years of study.

The ranking of each cultivar (based on average AWC and AC values) is displayed in Table 3.9. AWC was a less consistent measurement due to the highly-lodged monocultures of CDC Centennial and CDC Mozart (Figure 3.7B). Since competitive differences were only detected at SK sites, the cultivar ranking is constructed from those sites and not from the AB sites. SW Midas, Camry, Stratus, and Reward consistently rank among the lowest for both AWC and AC (Table 3.9 and Figure 3.9). CDC Striker, Cutlass, and CDC Leroy ranked intermediate for AWC (5^{th}, 6^{th}, and 9^{th}) and AC (6^{th}, 8^{th}, and 7^{th}), respectively. CDC Centennial and CDC Patrick consistently ranked among the most competitive of the cultivars included in this study, exhibiting high AWC and AC values (Table 3.9; and Figure 3.9). Differences were not due to market class, however, as single degree of freedom contrasts between yellow and green seed coat colors were not significant for AWC or AC.

Table 3.7 *P*-values obtained from analysis of variance of field pea ability to withstand competition (AWC) and ability to compete (AC) and Saskatchewan and Alberta in 2012 and 2013.

Province	AWC	AC
Alberta		
Cultivar	NS	NS
Saskatchewan		
Cultivar	*	***

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels. NS denotes not significant.

Table 3.8 Values for ability to withstand competition (AWC) and ability to compete (AC) for field pea cultivars grown in Saskatchewan in 2012 and 2013. Data are means with HSD given.

	SK	
Cultivar	AWC	AC
CDC Mozart	88	78
CDC Meadow	72	83
Cutlass	75	80
Reward	62	69
SW Midas	69	77
CDC Centennial	91	82
CDC Patrick	81	83
Camry	69	75
Cooper	71	82
CDC Sage	78	79
CDC Striker	76	81
Stratus	71	73
CDC Leroy	71	81
CDC Dakota	73	86
Mean	75	79
HSD (0.05)	27	9

3.3.11 Correlations between traits

Correlation analysis identified several significant correlations between variables in this study (Tables 3.10 and 3.11). As expected, crop and weed biomass were highly correlated ($P > 0.001$) with field pea leaf area and vine length at SK sites and vine length at AB sites. Crop yield and weed seed production were also highly correlated with several others traits measured in this study. Although statistically significant, none of these correlations were strong in magnitude (>

0.7; Fox et al, 1997), which suggests that none of the traits measured in this study correlated with competitive ability. A strong correlation was detected between AC and weed seed production, which was both highly significant ($P < 0.001$) and ranged between 0.69 and -0.94 at the AB and SK sites, respectively. Likewise, correlations between AWC and field pea crop yield were highly significant ($P < 0.001$) and ranged between 0.75 and 0.60 at the SK and AB sites, respectively.

Table 3.9 Ranking of ability to withstand competition (AWC) and compete (AC) for pea cultivars grown at sites in SK and AB. Data ordered by overall rank of AC, then by rank of AWC.

	AWC	AC
Cultivar	Rank	Rank
CDC Dakota	7	1
CDC Patrick	3	2
CDC Meadow	8	3
Cooper	10	4
CDC Centennial	1	5
CDC Striker	5	6
CDC Leroy	9	7
Cutlass	6	8
CDC Sage	4	9
CDC Mozart	2	10
SW Midas	13	11
Camry	12	12
Stratus	11	13
Reward	14	14

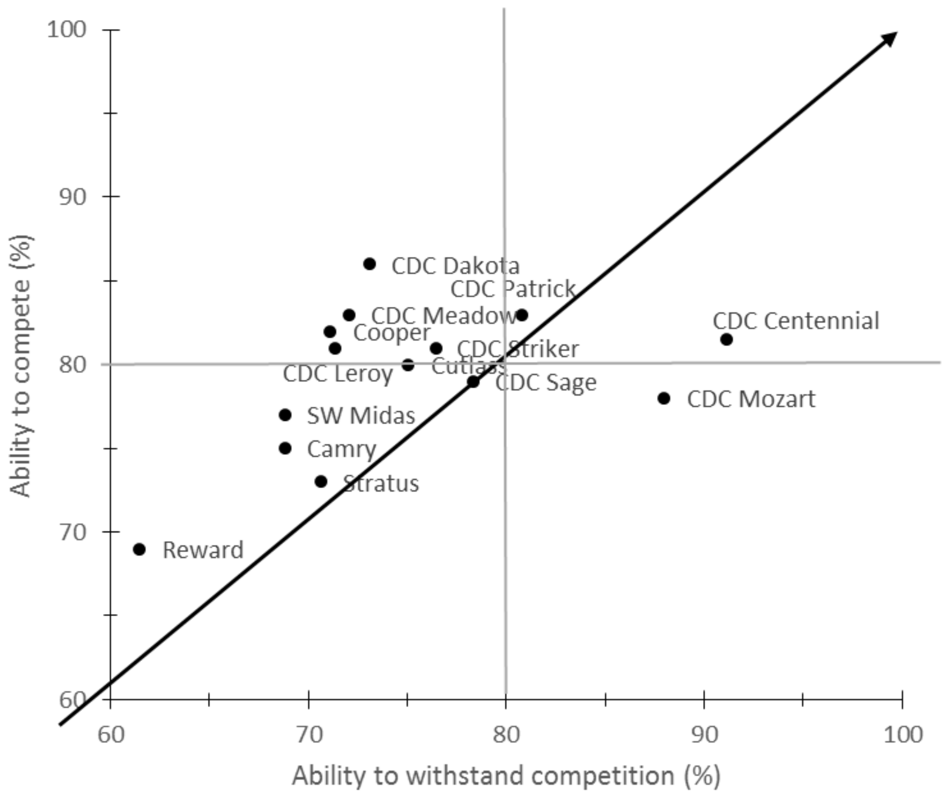


Figure 3.9 Scatterplot of ability to compete (AC) versus ability to withstand competition (AWC). Data are averaged across all site-years in Saskatchewan. The arrow points in the direction of increasing competitive ability. Gray lines represent: (1) on the x-axis (AWC), 20% yield loss and (2) on the y-axis (AC), 20% model weed seed yield.

Table 3.10 Spearman's correlation coefficients and *P* – values among leaf area index (LAI), petiole and tendril area (PTA), vine length (VL), crop biomass (CBM), weed biomass (WBM), crop thousand seed weight (TKW), crop yield (CYLD), weed yield (WYLD), ability to withstand competition (AWC), and ability to compete (AC) at SK in 2012 and 2013.

	LAI	PTA	VL	CBM	WBM	TKW	CYLD	WYLD	AWC	AC
LAI	1.00									
PTA	0.74***	1.00								
VL	0.41***	0.22*	1.00							
CBM	0.32***	0.36**	0.21***	1.00						
WBM	-0.36***	-0.10NS	-0.37***	-0.38***	1.00					
TKW	-0.18**	0.09NS	-0.59***	-0.10NS	0.28**	1.00				
CYLD	0.41***	0.48***	0.34***	0.41***	-0.50***	-0.13*	1.00			
WYLD	-0.33***	-0.01NS	-0.47***	-0.52***	0.76***	0.045*	-0.51***	1.00		
AWC	0.40***	0.25NS	0.35***	0.32***	-0.51***	-0.16*	0.60***	-0.54***	1.00	
AC	0.44***	0.23NS	0.54***	0.48***	-0.76***	-0.43***	0.70***	-0.94***	0.62***	1.00

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels. NS denotes non-significant.

Table 3.11 Spearman's correlation coefficients and *P* – values among leaf area index (LAI), petiole and tendril area (PTA), vine length (VL), crop biomass (CBM), weed biomass (WBM), crop thousand seed weight (TKW), crop yield (CYLD), weed yield (WYLD), ability to withstand competition (AWC), and ability to compete (AC) at AB in 2012 and 2013.

	LAI	PTA	VL	CBM	WBM	TKW	CYLD	WYLD	AWC	AC
LAI	1.00									
PTA	0.69***	1.00								
VL	0.06NS	-0.01NS	1.00							
CBM	0.04NS	0.22*	-0.32***	1.00						
WBM	0.02NS	-0.06NS	0.52***	-0.76***	1.00					
TKW	-0.09NS	0.11NS	-0.05NS	-0.10NS	0.19NS	1.00				
CYLD	0.16*	0.31**	-0.08NS	0.54***	-0.54***	0.22***	1.00			
WYLD	0.11NS	-0.10NS	0.29**	-0.57***	0.52***	0.34***	-0.46***	1.00		
AWC	-0.13NS	0.14NS	-0.41***	0.69***	-0.61***	-0.16NS	0.75*	-0.56***	1.00	
AC	-0.01NS	0.04NS	0.26**	0.11NS	-0.15NS	-0.23*	0.25**	-0.69***	0.15NS	1.00

3.4 Discussion

The results of this study showed that some differences in competitive ability do exist among semi-leafless field pea cultivars. Competitive differences between field pea cultivars were observed at three (SK sites) of the five site-years in which this study was conducted. At these sites, there was no difference in the ability of the cultivars to reduce model weed biomass (Table 3.5); however model weed seed production was reduced by 41% (496 kg ha^{-1}) when comparing CDC Dakota (most competitive cultivar) to Reward (least competitive cultivar) (Figure 3.8). Cultivars differed in their biomass production and this was not influenced by the presence or absence of model weeds, as they were not correlated with biomass production or competitive ability. Additionally, CDC Dakota, CDC Patrick, and CDC Meadow exhibited the highest AC values, while CDC Centennial, CDC Mozart, and CDC Patrick were among the best cultivars for AWC values. Plotting these ranks against one another in Figure 3.9, we can deduce that CDC Patrick, CDC Centennial, and CDC Mozart were among the most competitive cultivars in the study, while all other cultivars examined exhibited low to intermediate competitive abilities.

It is possible that the observed differences between sites was due to variations in soil properties and environmental conditions (Tables 3.1 and 3.4). For example, organic matter content of the soil at AB ranged from 10 to 10.7% and was approximately three- to five-fold greater than at SK sites (2.1 to 3.6%). Precipitation events also differed during the growing season at the different sites (Table 3.4). Differences could also be due to emergence timing of weeds, as early emergence can provide a competitive advantage to weeds (Bosnic and Swanton, 1997; Forcella et al., 2000). However, in this study those cultivars with delayed emergence did not necessarily exhibit the greatest above-ground biomass (Figure 3.5), grain yield (Figure 3.8), AWC, or AC (Table 3.9). It is possible that field densities of model weeds were too low to induce strong competitive effects since competition from model weeds did not significantly reduce yield when compared to the pea monoculture (Table 3.5 and 3.6). Model weed densities ranged from 33 to 42 plants m^{-2} at AB and 34 to 44 plants m^{-2} at SK (data not shown), but model weed target densities were 40 to 50 plants m^{-2}. Previous research has shown that field pea is sensitive to weed densities, and the competitive effect of weeds on field pea crops in known to be a function of weed species and density. For example, Wall et al. (1991) found that 20 plants m^{-2} of wild mustard reduced field pea yield by 2 to 35%. Likewise, Spies et al. (2011) reported field pea yield losses up to 26% with 50 plants m^{-2} of wheat and canola (25 plants m^{-2} each) in competition with field pea.

Results from this study demonstrate that although competitive differences existed among semi-leafless field pea cultivars (Tables 3.8, 3.9, and Figure 3.9), these differences were small in magnitude. Based on AC and AWC values, our data show that CDC Dakota and CDC Centennial generally had a higher competitive ability than most of the other cultivars, while Reward was consistently less competitive than most other cultivars (Figure 3.9). All of the other cultivars tended to be intermediate in their competitive abilities. Similar results have been reported in barley where a tall cultivar, cv. Virden, suffered the least yield loss (11%), and a semi dwarf cultivar, cv. Peregrine, exhibited the greatest yield loss (55%) (Watson et al., 2006). Tepe et al., (2005) reported a two-fold difference in yield loss between lentil cultivars in the presence of weed competition. McDonald (2003) noted that tall and normal leaf field pea cultivars were better able to withstand competition than short and semi-leafless cultivars. Likewise, Spies et al. (2011) documented a large difference in field pea yield loss between normal leaf and long vine-length cultivars compared with semi-leafless cultivars. Results from the current study contradict those of Spies et al. (2011) as cultivars with shorter vine lengths minimized yield losses in our study. One explanation for this is that the cultivars CDC Centennial and CDC Mozart were very prone to lodging in weed-free plots (Figure 3.7) and although the plot area was harvested carefully, some of the peas may have been shed or lost at harvest. This likely influenced the AWC calculation, meaning that less harvested field pea seed in the weed-free plots lead to higher AWC values.

In the current study, SW Midas, Camry, Stratus, and Reward ranked as the least competitive for both variables (AWC and AC), and these cultivars should not be recommended if high weed competition is expected. Alternatively, CDC Dakota, CDC Patrick, and CDC Meadow ranked among the best for model weed seed suppression, although they did not have the highest AWC values. Producers would be well advised to grow any of these cultivars if competition from weeds was expected to be substantial. Nevertheless, it is difficult to suggest a variety that was clearly better able to tolerate and withstand weed competition on a consistent basis. There appeared to be little relationship between the two metrics (AC and AWC), and cultivars that were ranked highly for one metric tended to be poorly ranked for the other. This is consistent with previous research by Harker et al. (2008) and Spies et al. (2011) who found that the highest yielding field pea cultivars under weed competition were not necessarily the highest yielding cultivars under weed-free conditions. However, conclusions drawn by Harker et al. (2008) and Spies et al. (2011) were based on comparisons between semi-leafless and normal leaf type field pea cultivars, whereas the present study only evaluated semi-leafless field pea cultivars.

The lack of varietal consistency observed in this study for AC and AWC values may not be surprising since correlations between AC and AWC were not significant at the AB sites and were not highly correlated at the SK sites (although they were statistically significant). While the reasons for this remain unclear, it suggests that AC and AWC are driven by different mechanisms. Because AC and AWC are surrogates for competitive effect and response, respectively, our data suggests that competitive response and effect are not two sides of the same coin as suggested by Wang et al. (2010). This concurs with other studies that also noted differing mechanisms may be driving competitive response and competitive effect (Miller and Werner, 1987; Goldberg and Landa, 1991; Keddy et al., 1994; Lamb et al., 2007). Competitive response may be driven by above-ground mechanisms as demonstrated by Afifi and Swanton (2012), who noted that low red to far-red light ratios reflected from neighbouring weeds can change the light quality intercepted by the crop (maize). In contrast, competitive effect may be driven by root competition; research by Lamb et al. (2007) determined that the addition of nitrogen significantly intensified below-ground competition. Research by Wang et al. (2010) found that the competitive effect under both low and high fertility explained approximately 80% of the variation in plant traits.

Strong correlations in this study were detected between AC and weed seed production as well as between AWC and field pea crop yield. This is not surprising considering that a high AC value should be indicative of a variety that smothers weeds and thus, minimizes weed growth. Likewise, cultivars with a high AWC should withstand competition and thus, produce reasonable yields even in the presence of weeds. These correlations show that AC and AWC are good metrics for determining field pea competitive ability and can be used by breeders as selection criteria for improved competitive ability. Published cultivar rankings would require breeders to include competitive ability into variety trials and in seed guides to help producers to select competitive cultivars. As suggested by Watson et al. (2006), publishing AWC and AC rankings separately would be beneficial in various production systems. AWC would be suitable in a conventional production system where crop yield is important and the use of herbicides and other agronomic practices helps to minimize the impact of competition from weeds and to reduce weed seed return. In organic crop production systems, where minimizing weed seed return is as important as crop yield, AC would be a critical metric for competitive cultivars. Nevertheless, given the lack of strong correlations detected between the measured traits and the competitive abilities of the cultivars, it is clear that none of the traits included in this study has a substantial role in conferring competitive ability in field pea. It is possible that the traits most important to field pea competitive ability were not measured in this study and that below-ground competition is important to competitive ability in field pea.

3.5 Conclusions

Semi-leafless field pea cultivars assessed in this study exhibited variation in competitive ability. However, competitive differences were only observed at the SK sites. CDC Dakota, CDC Patrick, and CDC Meadow were the top cultivars in their ability to compete and CDC Centennial, CDC Mozart, and CDC Patrick in ability to withstand competition, while Reward was consistently the poorest cultivar for both metrics. The results of inconsistent varietal competitiveness in this study indicate that AWC and AC may be driven by different mechanisms. None of the above-ground traits measured in this study were strongly correlated with competitive ability, implying that another mechanism not measured in this current study may be driving competitive ability.

4.0 Exploring the relative importance of above- and below-ground competition in semi-leafless field pea.

4.1 Introduction

Examining above- and below-ground plant interactions is vital to understanding plant competition, which involves both above- and below-ground competition for limited resources. Above-ground competition consists of vegetative organs competing for sunlight and space, while below-ground competition involves roots competing for both nutrients and water. Below-ground competition is size symmetric, meaning that plant competitiveness is proportional to size and thus, a large plant will cause a smaller plant to suffer a proportionately large loss in plant growth, while a smaller plant will have a minimal impact on the growth of a larger plant (Weiner et al., 1997; Schwinning and Weiner, 1998). In contrast, above-ground competition is size asymmetric (Weiner, 1985; Weiner and Thomas, 1986) as smaller plants do no influence the amount of sunlight acquired by larger plants, whereas larger plants disproportionately reduce incoming sunlight to smaller plants (Cahill and Casper, 2000). Depending on the plant species, above- or below-ground competition may place a plant at a competitive advantage, assisting the plant to acquire more resources than neighbours (Pavlychenko and Harrington, 1934). In this case the plant would be considered more competitive than its neighbour. Competition can further be divided into interspecific (plants of different species) and intraspecific (plants of the same species) competition (Donald, 1963).

The majority of plant competition takes place below-ground (Casper and Jackson, 1997). However, research on below-ground competition is limited due to the difficulty in observing root interactions. Below-ground traits important in competitive ability include root size and volume (Gaudet and Keddy, 1988), distribution (Dunbabin, 2007), and rate of resource uptake

(Dunbabin, 2007). Competition between plant roots occurs earlier than competition between shoots as plant roots establish earlier, grow more quickly, and compete with roots of neighbouring plants when grown in close proximity (Pavlychenko and Harrington, 1937). Root competition is thought to be more important to plant growth and development than shoot competition, especially with regard to crop-weed interactions (Pavlychenko and Harrington, 1937; Wilson, 1988). Cahill (2003) observed that the importance of below-ground competition could be demonstrated by the magnitude of reductions in plant growth. Research also showed that the addition of fertilizer decreased below-ground competition among plants and that the abundance of water and nutrients can intensify above-ground competition (Cahill 1999). Research on below-ground interactions between crops and weeds could thus be critical to the development of more competitive crop varieties (Brown and Scott, 1984; Mackay and Barber, 1986; Auf'm Erley et al., 2007; and Koscielny and Gulden, 2012).

Above-ground competition has been demonstrated to be of great importance to crop production in many crops (Appleby et al., 1976; Garrity et al., 1992; O'Donovan et al., 2000; Murphy et al., 2008). Traits such as plant height (Murphy et al., 2008; and Zerner et al., 2008) and leaf area (Cote et al., 1992; Radosevich et al., 2007) are key components of competitive crop stands. An interesting exception to this may be field pea, wherein semi-leafless cultivars lack true leaves and exhibit little overall variation in height. Spies et al. (2011) have shown that normal leaf cultivars pea cultivars were more competitive with wheat and canola (model weeds) than were semi-leafless cultivars. Similar research has also found that unsprayed normal leaf field pea cultivars can yield as much or more than semi-leafless cultivars that have received a herbicide application (Harker et al., 2008).

Thus, field pea presents an interesting case study in competitive ability and may be used as a model species to examine the importance of below-ground competitive ability in relationship to crop biomass and yield. Little is currently known about the importance of above- vs. below-ground competitive ability in field pea and therefore, potential exists to reveal novel mechanisms that may be used in breeding programs to improve the ability of field pea to compete with weeds.

A greenhouse study was undertaken to examine the nature of above- and below-ground interactions in semi-leafless field pea. Identifying the above- and below-ground responses of field pea to neighbouring plants is necessary to determine how the dynamics of competition influence field pea growth and development. Understanding this will aid in the identification of traits that may be important to developing more competitive field pea varieties that are better able to compete for resources. The objective of this study was to assess whether above- or below-ground competition is driving the response of pea plants to neighbours, as well as the competitive ability of field pea. We also wanted to evaluate the importance of specific traits that may be associated with any competitive differences in semi-leafless field pea. Quantification of the importance of above- vs. below-ground competition may suggest ways to alleviate the competitive pressure put on the less dominant crop species.

4.2 Materials and Methods

4.2.1 Experimental design, location, and procedures

A greenhouse experiment was conducted at the University of Saskatchewan at Saskatoon, SK, Canada from February to April, 2013 and from June to August, 2013. A two-factor, randomized complete block design with four replicates was utilized. Treatment factors included factorial combinations of two competitor species and four competition regimes. Each competitor species was grown with a focal plant of field pea cv. CDC Meadow. Competitor species included field pea (cv. CDC Dakota, intraspecific competitor) and a forage oat variety (cv. CDC Haymaker, interspecific competitor). The four competition regimes consisted of full competition, shoot competition, root competition, and no competition.

Experimental units consisted of five pots arranged in a crossed shape, each with a single plant per pot (Figure 4.1). CDC Meadow (focal plant) was arranged in the center pot, with the four surrounding pots comprised of competitor species of either field pea or oat. For competition regimes requiring below-ground separation (shoot competition and no competition) plants remained in their individual pots with no root interaction permitted among pots (Walker and King, 2009). When below-ground separation was not needed (root competition and full competition), the sides of the pots that were shared with another pot were removed and placed together in the crossed shape. Where above-ground competition was required, the above-ground plant characters were allowed to interact (shoot competition and full competition) but where above-ground separation was required (root competition and no competition), plant characters were separated using wire mesh (above-ground barrier), which was installed using wire mesh installed 10 d after planting. Above-ground barriers were made of 24 gauge galvanized welded iron mesh with 6mm openings (BEN-MOR Inc., Quebec, Canada). Wire mesh was cut into 60 cm by 52.5 cm pieces, and folded into a freestanding tube that fit into each pot. The above-ground barriers intercepted approximately 20% of the available light. Each experimental unit (five pots) was placed on pressure treated plywood and was re-randomized weekly to minimize environmental variability. Plants were not staked as this would influence the results of the study.

A 3:1 mixture of sand:topsoil was utilized as the potting medium (Table 4.1). The mixture was thoroughly mixed together and watered to field capacity before potting. Seeds were sown in 13 cm diameter (2 L) pots at a depth of 5 cm. All seeds were pre-germinated for 2 d before planting to ensure uniform germination and emergence. Field pea seeds were inoculated with the appropriate strain of rhizobium species Rhizobium (*Rhizobium leguminosarum* biovar viceae) at a rate of 0.2% w/w prior to planting. A square pot-planter, 13 cm in diameter, was constructed to ensure uniform planting depth, and that plants were equidistant and equiangular to each other to eliminate any bias that could influence the competitive outcome (Willenborg et al., 2005b). Neighbouring plants were spaced 13 cm from the focal plant. Where final emergence was less than the targeted density, seedlings from the spare pots were transplanted 3 d after emergence to compensate for germination and emergence that had failed.

Table 4.1 Soil test results for topsoil used for greenhouse study at Saskatoon, SK in 2013.

Soil properties	
pH	8.4
Nitrate (lb ac^{-1})	5
Phosphorous (lb ac^{-1})	>60
Potassium (lb ac^{-1})	>600
Sulfur (lb ac^{-1})	>48
Organic matter (%)	26.6

Greenhouse temperature in both experimental runs was maintained at 24/20°C day/night with an 18-h photoperiod. Artificial lighting was provided by 1000-W high-pressure sodium lamps with a photosynthetically active radiation (PAR) level below 1000 µmol m^{-2} s^{-1}, and were turned off when PAR was above 1300 µmol m^{-2} s^{-1}. Relative humidity was 38 and 59% for the first and second experimental runs, respectively.

Plants were monitored daily and were watered to field capacity as necessary. Water soluble fertilizer (20-20-20, N-P-K) was applied in a 100 µg ml^{-1} solution at a rate of 11 kg ha^{-1} twice throughout each experimental run (bi-weekly). A limited fertility regime was imposed to ensure adequate competition between competitor and focal species.

Emergence timing was monitored daily by recording when plants emerged above the soil surface. Internode length was measured weekly as the length of three internodes (between the soil surface and epicotyl, 1^{st} node and 2^{nd} node, and 8^{th} node to 9^{th} node) using a caliper. All plants were harvested when the focal plant reached the early flowering stage (March 25^{th}, 2013 and July 22^{nd}, 2013). At this time, vine length was measured for the focal plants from the soil surface to the top of the apical meristem, and leaf area was determined by cutting all of the leaves off each focal plant and running them through a leaf area meter (model LI3100, Lincoln, Nebraska). In the second experimental run, petiole and tendril area of the focal plants was also included in the leaf measurement. Above-ground biomass was taken for both focal and competitor plants by cutting the plants at the soil surface, placing them in paper bags, drying them at 40°C for 48 h, and then weighing them. Root biomass was measured for both focal and competitor plants by carefully removing the soil from the roots, soaking them in water for 3-5 min and carefully separating the roots of each plant. Once separated, roots were placed into paper bags, dried for 48 h at 40°C, and weighed.

4.2.2 Statistical Analysis

Analysis of Variance (ANOVA) was performed using the MIXED model procedure of SAS (SAS Institute, 2011). Degrees of freedom were calculated using the SATTERTHWAITE approximation. Residuals were initially tested for normality with the UNIVARIATE procedure, while homogeneity of error variance was confirmed using Levene's test in SAS (SAS Institute, 2011). To satisfy the assumptions of ANOVA, competitor plant emergence and focal plant root to shoot (R:S) ratio were $\log_{10}$ transformed for analysis and then back-transformed for presentation. Fixed effects in the model were comprised of the four competition regimes, competitor species, and their interaction while the random effects consisted of block nested in experimental run, experimental run, and the combinations of experimental run by fixed effects interactions. The random effects were examined using COVTEST to see if experimental runs could be combined; results could be combined for all response variables. Means separation was performed using Tukey's HSD at $P < 0.05$. None of the interactions were significant for the focal plant; however the emergence by competition regime interaction was significant for the competitor species and thus, data were analyzed within the interaction.

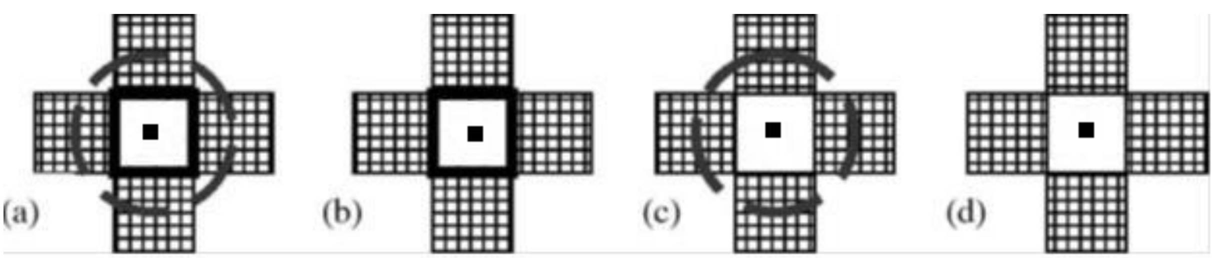


Figure 4.1. Layout of competition treatments for greenhouse study. Dotted pattern represents target species (field pea) and grid pattern represents competitor treatments (field pea or tame oat). The solid line represents the below-ground barrier (black line in square shape around focal pea plant) while the dashed line represents the above-ground barrier (dashed line around solid line). a) No competition – above - and below-ground barriers present b) shoot competition – below-ground barriers present c) root competition above- ground barriers present d) full competition – no barriers present. Adapted from Walker and King (2009).

4.3 Results

4.3.1 Focal and competitor species emergence

Focal plant emergence was not different between competition regimes (Table 4.2). Competitor species differed in their emergence timings ($P < 0.001$) and the competitor species by competition regime interaction was significant (Table 4.3). The differences occurred because competitor field pea (CDC Dakota) emerged four days after sowing, while tame oat emerged only three days after sowing (Figure 4.2), regardless of the competition treatment (Figure 4.3). Focal plant emergence was not significantly different between competition regimes, competitor species, or the competition treatment by competitor species interaction.

Table 4.2 P-values for focal plant emergence (FEMER), focal plant vine length (FVL), focal plant leaf area (FLA), focal plant petiole and tendril area (FPTA), focal plant shoot biomass (FSBM), focal plant root biomass (FRBM), and focal plant root:shoot ratio (FR:S) in a greenhouse experiment at Saskatoon, SK in 2013.

Source	FEMER	FVL	FLA	FPTA	FSBM	FRBM	FR:S
				P values			
Competitor (C)	0.515	0.585	0.624	0.382	0.908	0.438	0.602
Competition regime (CR)	0.271	0.301	0.281	0.007**	0.039*	0.001***	0.001***
C X CR	0.881	0.381	0.808	0.648	0.760	0.675	0.727
Run (R)	0.314	0.614	0.182	0.610	0.205	0.445	0.239
Rep	0.054	0.477	0.112	0.270	0.188	0.193	0.308
R X C	0.234	0.240	0.186	0.311	0.187	0.337	0.256
R X CR	0.482	0.440	0.482	0.275	0.316	0.197	0.414
R X C X CR	0.457	0.302	0.299	0.416	0.328	0.212	0.294

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels. NA denotes not applicable.

4.3.2 Light intercepting traits

Several traits that collectively provide light interception were measured in this study including focal plant vine length (FVL), focal plant leaf area (FLA), and focal plant petiole & tendril area (FPTA). Although only measured in one experimental run, FPTA was significantly different between competition regimes but not between neighbour species (Table 4.2). The greatest petiole and tendril area in the focal plant species occurred under shoot competition, regardless of interspecific or intraspecific competition. Shoot competition resulted in 61% and 40% more petiole and tendril area than the no and root competition treatments, respectively (Figure 4.4). There was no interaction between the competition regime competitor species with regard to FPTA (Table 4.2). Likewise, the main effects of competitor species, competition regime, and their interaction were not significant for FVL or FLA in the focal plant species (Table 4.2).

Table 4.3 P-values for competitor emergence (COEMER), competitor shoot biomass (CSBM), competitor root biomass (CRBM), and competitor root:shoot ratio (CR:S) in a greenhouse experiment at Saskatoon, SK in 2013.

	COEMER	CSBM	CRBM	CR:S
	P values			
Competitor (C)	< 0.001***	0.012*	0.002**	0.003**
Competition regime (CR)	0.284	0.656	0.132	0.009**
C X CR	0.023*	0.815	0.352	0.171
Run (R)	0.287	0.387	0.279	0.365
Rep	0.239	0.259	0.248	0.292
R X C	0.457	0.177	0.262	0.422
R X CR	0.485	0.362	0.366	0.220
R X C X CR	0.327	0.274	0.141	0.292

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels. NA denotes not applicable.

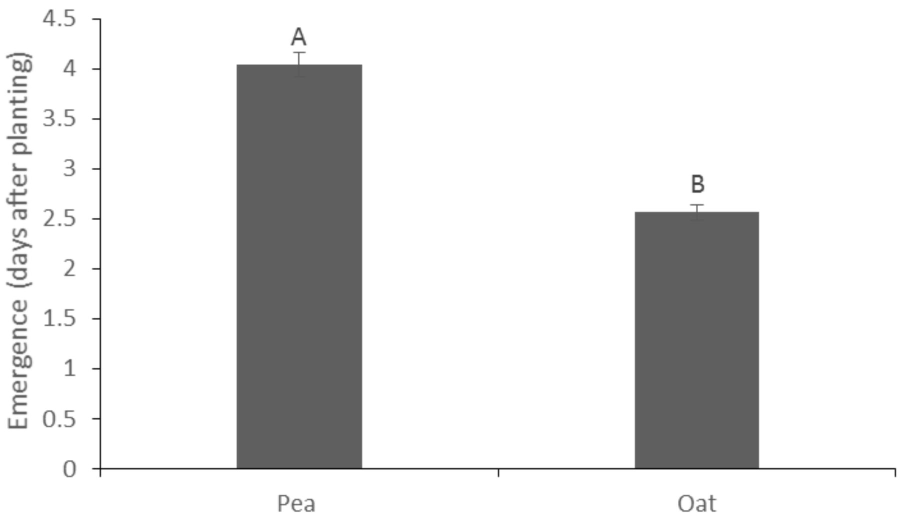


Figure 4.2 Competitor species emergence when grown in competition with a single focal pea plant in a greenhouse experiment. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference based on $HSD_{0.05}$.

4.3.3 Shoot (above-ground) biomass

Focal plant shoot biomass differed ($P < 0.05$) among competition regimes (Table 4.2). Shoot biomass in focal plants was 73% greater when only shoot competition was permitted compared with where no competition occurred (Figure 4.5). Full and root competition treatments were intermediate, and were not significantly different from either the shoot or the no competition regimes. Neither competitor species nor the interaction between competitor species and competition regime were significant for focal pea shoot biomass (Table 4.2).

As expected, shoot biomass production differed significantly ($P < 0.05$) between competitor species (Table 4.2). Field pea as a competitor species produced 35% more shoot biomass than tame oat, regardless of competition regime (Figure 4.6). Neither competition regime nor the interaction between competitor species and competition regime were significant for competitor species shoot biomass (Table 4.3).

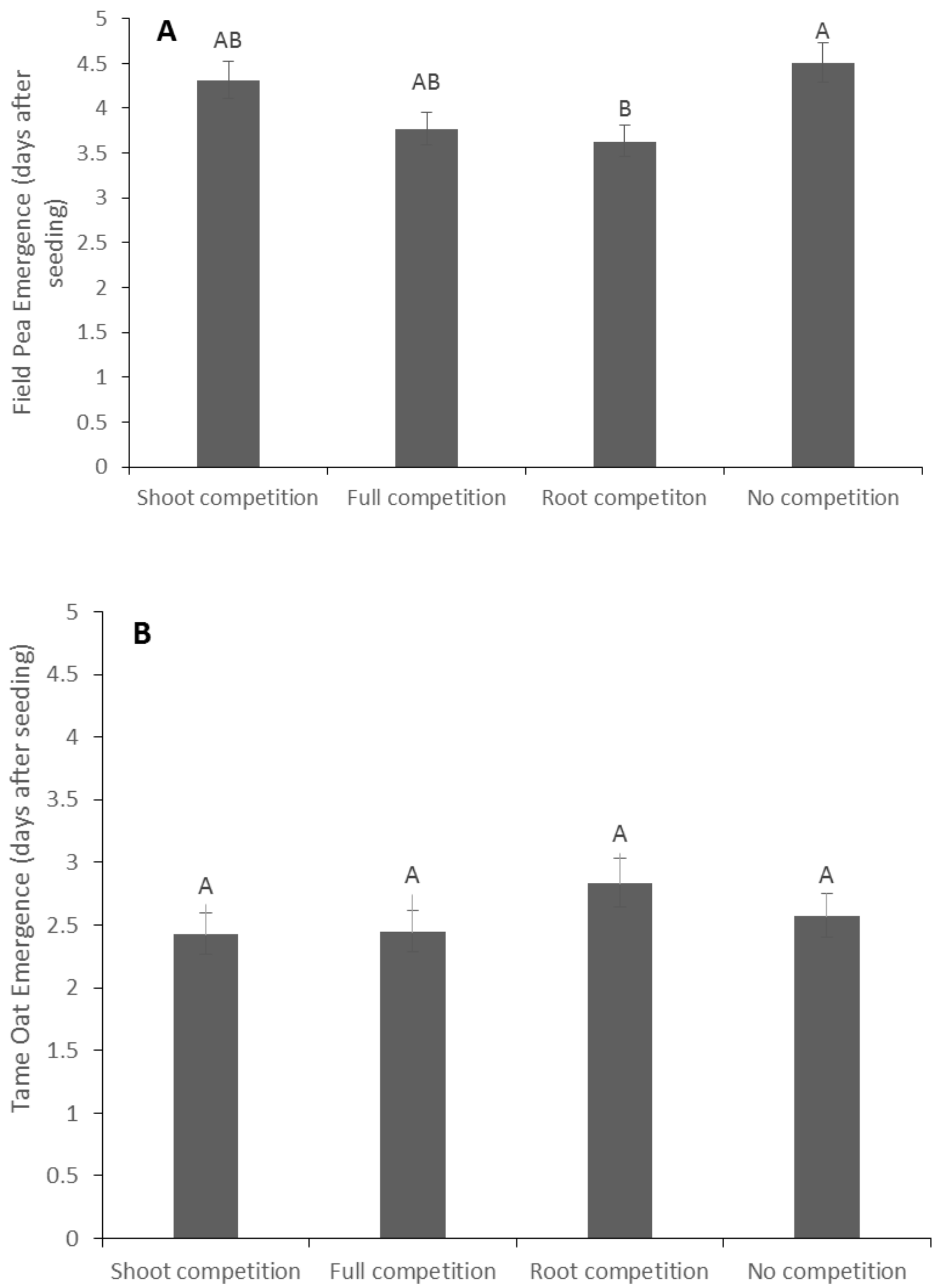


Figure 4.3 Competitor species emergence for (A) pea and (B) oat, grown in competition with a single focal pea plant in a greenhouse experiment. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference at $HSD_{0.05}$.

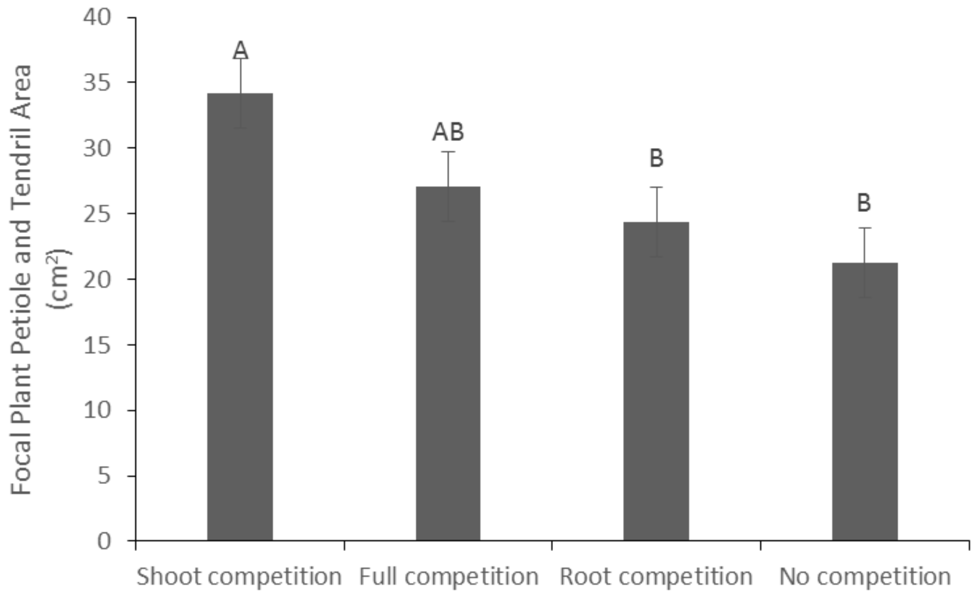


Figure 4.4 Petiole and tendril area for various competition regimes in a greenhouse experiment. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference at $HSD_{0.05.}$

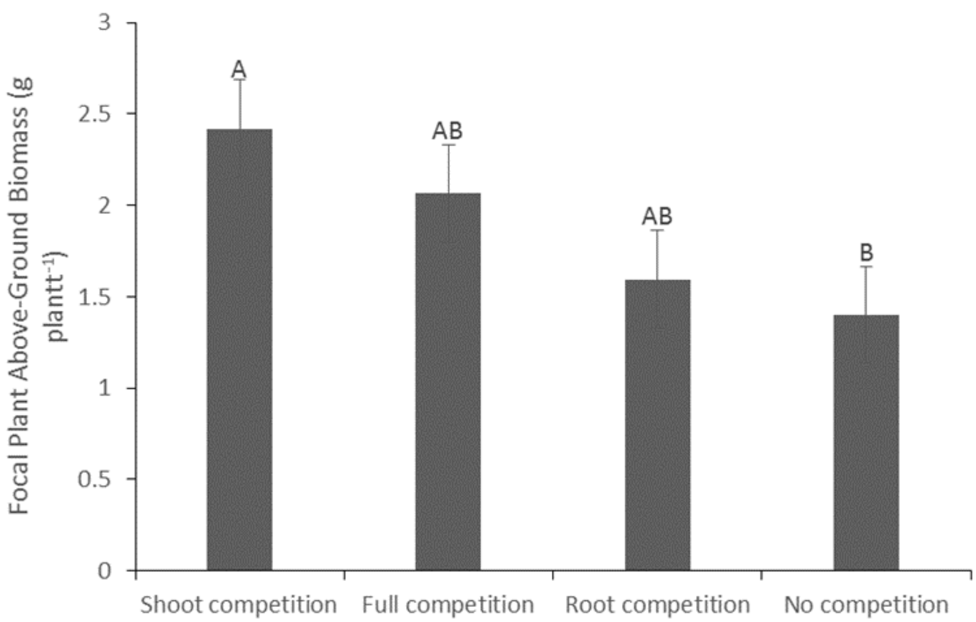


Figure 4.5 Focal plant shoot biomass among various competition regimes in a greenhouse experiment. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference at $HSD_{0.05.}$

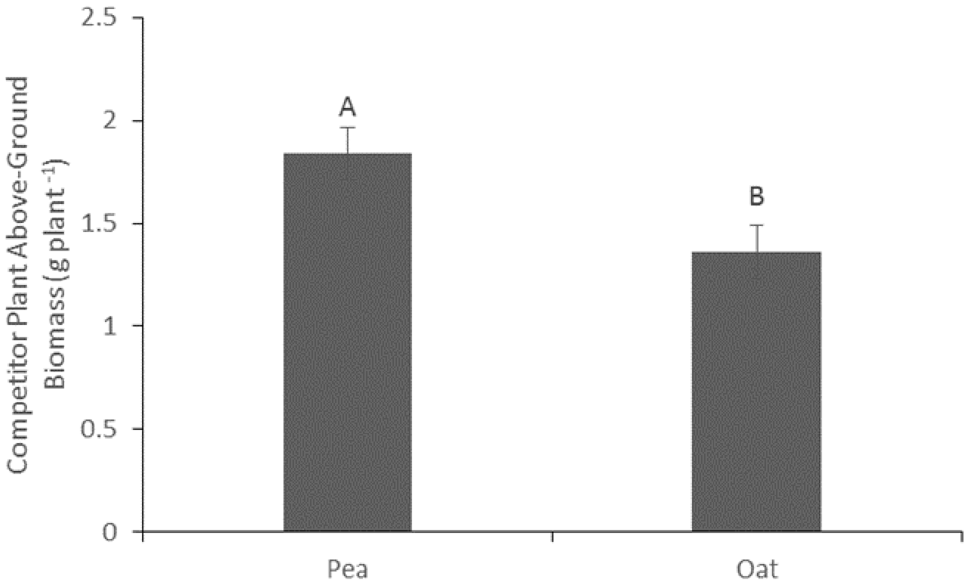


Figure 4.6 Competitor species shoot biomass when grow in competition with a single focal pea plant in a greenhouse experiment. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference at $HSD_{0.05}$.

4.3.4 Root (below-ground) biomass

Focal plant root biomass differed among competition treatments ($P < 0.001$) (Table 4.3). Treatments that permitted root competition always resulted in significantly lower focal plant root biomass than those that permitted shoot competition, regardless of competitor species (Figure 4.7). In fact, root biomass of the focal plant was 125% greater in the shoot competition treatment than in the root competition treatment (Figure 4.7). Root biomass of the focal plant did not differ between the no competition treatment and the root and full competition treatments, which suggests that the focal plant increased the production of root biomass in response to the presence of above-ground competition from the competitor species. Competitor species did not affect root biomass production in the focal plant species (Table 4.3).

Competitor species root biomass differed between species ($P < 0.01$) but not among competition regimes (Table 4.3). Tame oat produced 75% more root biomass than field pea, regardless of competition regime (Figure 4.8). The interaction between competition regime and competitor species was not statistically significant (Table 4.2).

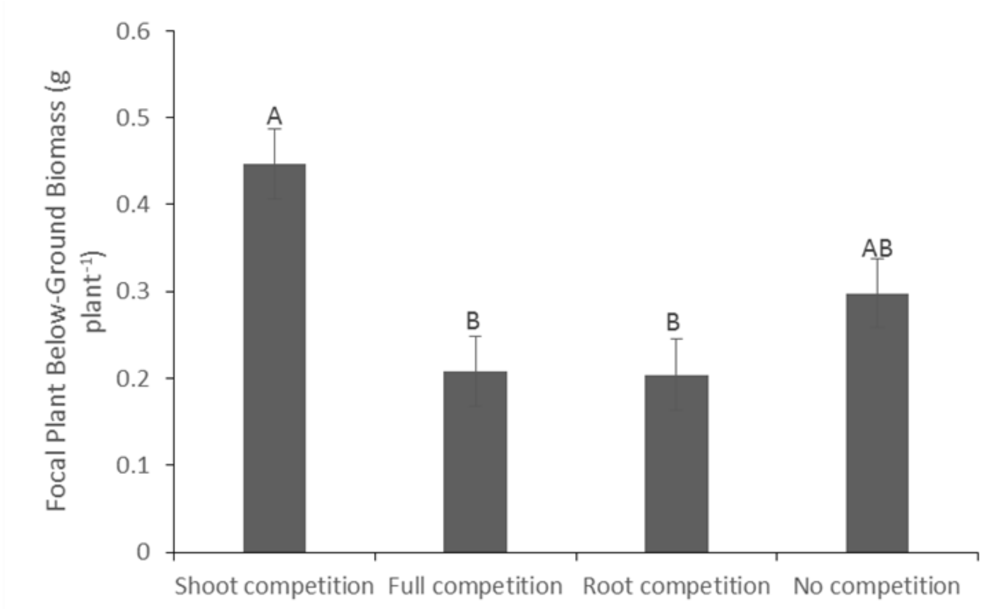


Figure 4.7 Focal plant root biomass among various competition regimes in a greenhouse experiment. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference at $HSD_{0.05.}$

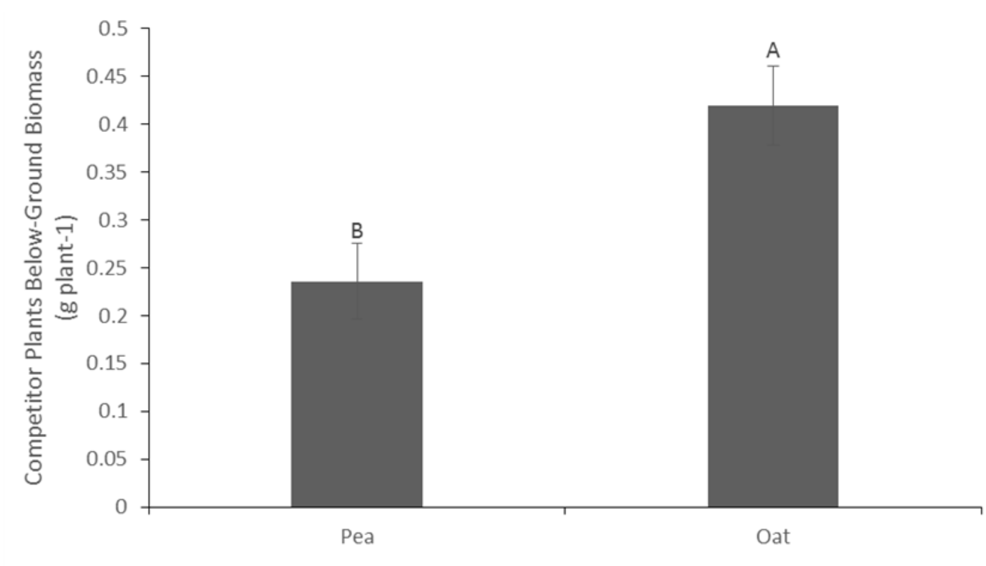


Figure 4.8 Competitor species root biomass when grown in competition with a single focal pea plant in a greenhouse experiment. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference at $HSD_{0.05.}$

4.3.5 Root:shoot (R:S) ratio

Focal plant root to shoot ratio (R:S) differed ($P < 0.001$) between competition regimes (Table 4.2). The largest R:S ratios were observed in the shoot only competition treatment (0.41) and the no competition (0.27) treatments, and the shoot competition treatment had a higher ($P < 0.001$) R:S ratio than either the full or root competition treatments (Figure 4.9). R:S ratios for focal pea plants were more than 2-fold greater under shoot competition than under root competition or full competition treatments. Root:shoot ratio of focal pea plants was not affected by competitor species, nor was there an interaction between competitor species and competition regime (Table 4.2).

Competitor species differed with regard to R:S ratios as oat exhibited two-fold greater R:S than field pea (Figure 4.10). The R:S ratios of competitor species also differed significantly ($P < 0.01$) among competition regimes, although no significant interaction between main effects was observed (Table 4.3). Both competitor species exhibited the highest R:S ratios in the no competition treatment (0.34) and the lowest R:S ratios in the full competition treatment (0.18) (Figure 4.11); this equated to an 89% reduction in R:S across treatments. No differences in competitor R:S ratios were observed between the full and root competition treatments, which suggests that plants of both species invested less in root production in treatments where roots were allowed to interact below-ground (full and root only competition regimes). There was no significant interaction between the main effects in regards to competitor species R:S ratios (Table 4.3).

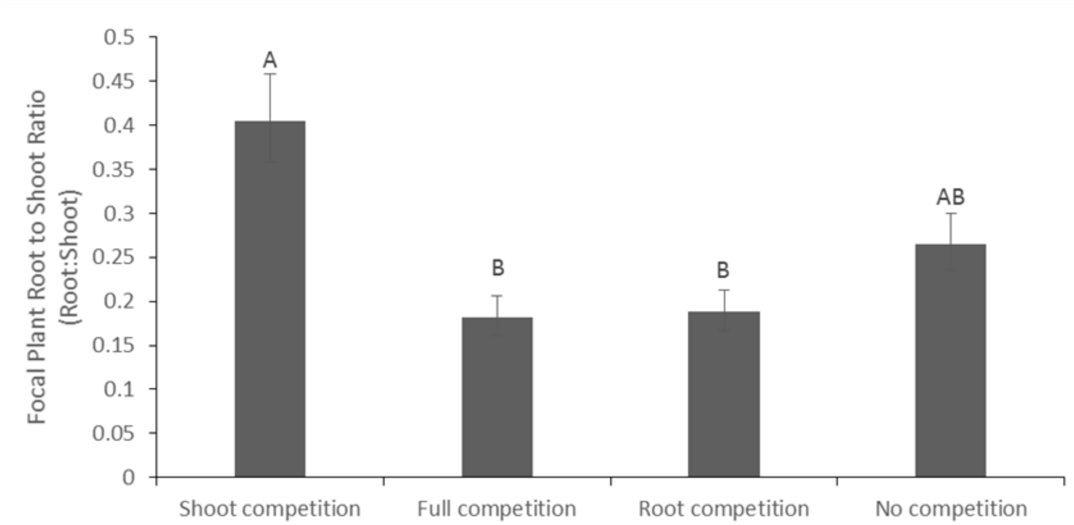


Figure 4.9 Focal plant root:shoot ratio among various competition regimes in a greenhouse experiment. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference at $HSD_{0.05.}$

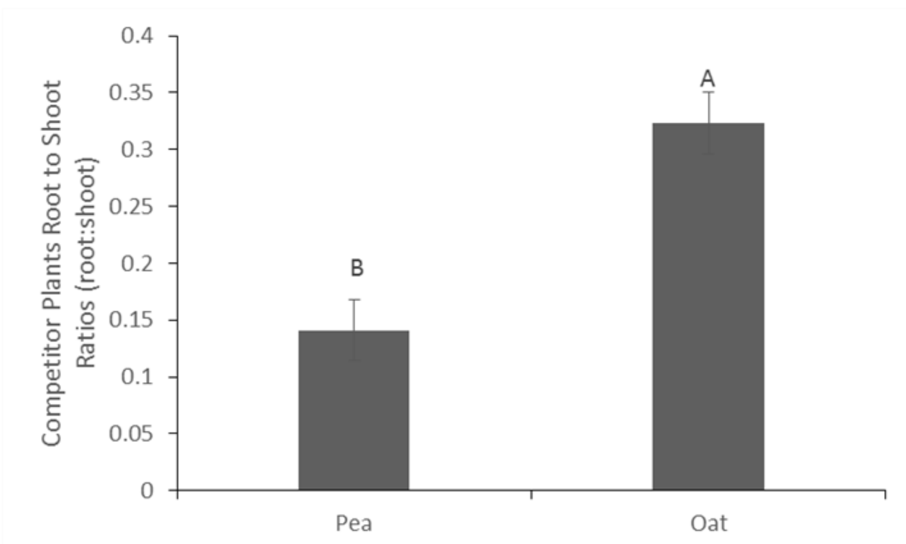


Figure 4.10 Root:shoot ratios for competitor species when grown in competition with a single focal pea plan in a greenhouse experiment. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference at $HSD_{0.05.}$

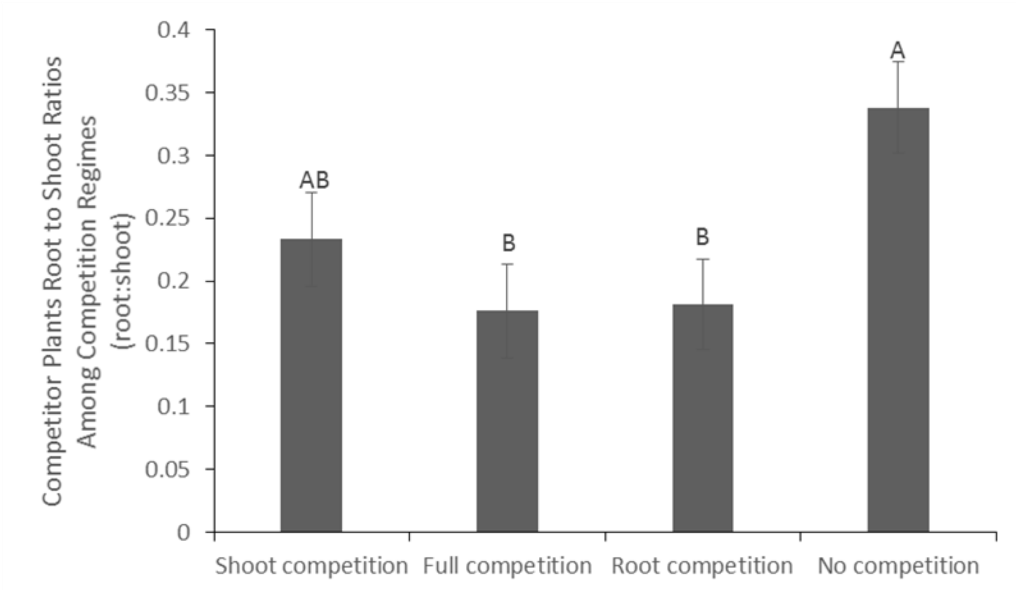


Figure 4.11 Competitor plants root:shoot ratios among various competition regimes, when grown in competition with a single focal pea plant in a greenhouse experiment. Error bars represent the standard error of the least squares means. Similar letters indicate no significant difference at $HSD_{0.05.}$

4.4 Discussion

The results from this experiment demonstrate the importance of below-ground competition, as significant decreases in focal plant root biomass were observed whenever root interactions were permitted (Figures 4.7). This agrees with Cahill (2003) who also reported that competition below-ground reduced plant growth. Focal plant root and shoot biomass were always greatest under shoot competition (Figure 4.5 and 4.7) and in all instances, the focal plant did not respond differently to the presence of different competitor species. Focal plant R:S ratios correlated with focal plant root and shoot biomass, as the R:S ratio decreased similarly under root competition and full competition. Consequently, focal plant R:S ratios were also highest under shoot competition and were significantly lower when below-ground interaction was permitted (Figure 4.9). Our results agree with Walker and King (2009) who observed reduced

R:S ratios when below-ground competition was permitted, thus demonstrating the importance of below-ground competition and its overall importance for plant growth and competitive ability.

In this study, the focal plant did not adjust above-ground traits (leaf area and plant height) to intercept more light when grown under different competition regimes. This suggests that there was no response from these above-ground traits to the varying competition regimes. This corroborates the findings of other studies including a competition experiment studying *Dactylis glomerata* L. (Eagles, 1972). The authors noted greater leaf area when plants were grown under full competition and root competition (Eagles, 1972). Likewise, research by Satorre and Snaydon (1992) reported that shoot competition had little effect on plant height when spring cereal crops competed with wild oat both above- and below-ground. Common milkweed (*Asclepias syriaca* L.) height was significantly reduced by root and shoot competition, yet full competition was most detrimental to shoot biomass (Evetts and Burnside, 1975). Similarly, Walker and King (2009) observed significant decreases in kura clover leaf area and plant height under root and full competition regimes. Although there has been no research on the response of field pea to below- and above-ground competition, the aforementioned studies do demonstrate the importance of below-ground competition in different plant species.

When competition was permitted in the shoot competition only treatments, the focal pea plant responded by producing considerably more shoot biomass due to the presence of below-ground barriers and neighbours. The corresponding increase in petiole and tendril area was likely attributable to the increase in focal plant shoot biomass (Figure 4.4). This increase in the intensity of above-ground competition in the absence of root competition suggests that competition above-ground may be important to field pea competitive ability only when there is no root intermingling. It may also indicate that competition for light was more intense than competition below-ground given the magnitude of the responses in root and shoot biomass. Bloom et al. (1985) observed that plants change their phenology to allocate more biomass to traits that best acquire limiting resources. Thus, the plants in this study may have shifted their allocation to shoot biomass when light became limiting. Walker and King (2009) documented an 18% increase in kura clover shoot biomass under shoot competition treatments compared with no competition; root competition and full competition treatments produced significantly lower shoot biomass in competition with meadow bromegrass (*Bromus biebersteinii* L.). Similarly, white persicaria (*Polygonum lapathifolium* L.) competing above-ground with barley showed increased leaf-area ratios and leaf-areas compared to when it was grown without competition (Aspinall, 1960).

Researchers have concluded that root competition is of greater importance than shoot competition (Litav and Isti, 1974; Casper and Jackson, 1997). There is support for this observation in the current study as root interactions (below-ground competition) caused large reductions in focal plant root biomass (Figure 4.7), suggesting intense competition for below-ground resources. The root interactions caused the focal plant to allocate more resources to vegetative production, which also intensified above-ground competition. It is noteworthy that competitor species differed in their root biomass production (Figure 4.8), yet the focal plant did not respond to competitor species identity. This suggests that the competitor signalling mechanism is not species-specific and is likely a response to the presence of neighbours and not to their identity.

Shoot competition treatments in the current study prompted greater root biomass accumulation (Figure 4.7); however root biomass was significantly reduced with removal of the below-ground barriers. This suggests that the focal plant avoided root interactions, and this may be indicative of an avoidance strategy by the focal pea plant in order to expend resources where competition is less intense. This finding agrees with other studies that have reported that biomass allocation within a plant under competition from neighbours is influenced by the intensity of competition. In this scenario, the plant will utilize resources to accumulate the biomass necessary to acquire additional limited resources (Agren and Franklin, 2003; Wilson, 1988; Bloom et al., 1985).

While the full competition treatment would be expected to have the fewest available resources, root biomass and R:S ratios were not different from those produced in the root competition or no competition treatments. They were only significantly different in the shoot biomass treatment, which suggests that interactions above-ground have a significant impact on root biomass. In these treatments the focal plant appeared to have adjusted allocation of resources to root production at the expense of shoot production. Such a response may be driven by red:far-red (R:FR) light signalling, as has been observed by others (Rajcan et al., 2004; Liu et al., 2009; Afifi and Swanton, 2012). Light quality is an important aspect of crop-weed competition as light rich in far-red wavelengths (low R:FR) signals the presence of neighbours; this typically results in shade avoidance by the plant (Rajcan et al., 2004; Liu et al., 2009; Afifi and Swanton, 2011). In addition to shade avoidance, the crop plant undergoes physiological changes in response to low R:FR ratio including a reduction in anthocyanin content and an accumulation of hydrogen peroxide in the first leaf (Afifi and Swanton, 2012). However, it is also possible that the focal plants in this study responded similarly to root competition as they did to full competition because root interactions occurred prior to above-ground interactions. Spacing between the plants and the use of pots with edges that extended above the soil surface may have contributed to a delay in the above-ground sensing of neighbouring plants, causing root interactions to occur prior to shoot interactions. This has been reported in several previous studies (Pavlychenko and Harrington, 1937; Rhodes and Stern, 1976; Casper and Jackson, 1997; Walker and King, 2009). Future research should be conducted using minirhizotrons to examine whether root interactions occur prior to shoot interactions in field pea.

4.5 Conclusions

This study showed that below-ground interactions play an important role in semi-leafless field pea competitive ability. Nevertheless, focal plants responded more to the presence of above-ground neighbours, as the magnitude of the increases in root and shoot biomass (and R:S ratios) were greatest in the shoot competition treatments. Root intermingling (below-ground competition) resulted in plants allocating more resources to shoot production at the expense of root production as evidenced by lower R:S ratios. The results also demonstrated that field pea plants do not respond to the identity of neighbours. That is, the response of focal pea plant to intraspecific competition was similar to interspecific competition, regardless of whether interactions occurred above or below the soil surface.

The results of this research should provide us with an improved understanding of the interactions between field pea and weeds. In the long-term, this research could benefit producers via improvements in the competitive ability of semi-leafless field pea cultivars by reducing yield loss and increasing weed suppression. The results will also be important to plant breeders, who may consider using the response of field pea plants to above-ground neighbours as a selection criteria in breeding programs. Furthermore, this research highlights the need to assess the below-ground competitive ability of field pea plants as selection criteria in breeding programs.

5.0 General Discussion

5.1 Field pea competitive ability and the importance of below-ground competition

Research from this thesis showed that field pea cultivars differed in their ability to tolerate and suppress model weeds at three site-years (Table 3.5). At these site-years, a substantial difference was observed between the cultivars in their ability to withstand competition and ability to compete values and model weed seed production was reduced by 41% (496 kg ha^{-1}). These results suggest that AWC and AC do reflect the ability of cultivars to withstand competition as well as to suppress the vegetative and reproductive growth of weeds (Tables 3.10 and 3.11).

Field pea competitive ability in this study did not differ at the AB sites, and this may be due to environmental conditions at those sites. In July of 2012, Edmonton received a substantial amount of rain and hail (Table 3.4). Previous research has shown that under differing environmental conditions, plants will vary in their competitive ability and growth habits (Melander, 1993; Lemerle et al., 1995; Cousens and Mokhtari, 1998; Seavers and Wright, 1999). Wall et al. (1991) reported that precipitation plays a large role in field pea competitive ability, with the greatest yield losses occurring under normal to high rainfall. In addition, the sites at St. Albert were harvested using a hand sickle, which cut only 1.5 m^{-2} from each plot compared with the 6.58 m^{-2} at the SK sites. It is possible that the harvested plot area in AB was too small. Another possible explanation for the lack of competitive differences at AB is that the model weed density was substantially lower at the AB sites than at the SK sites. Perhaps increasing the model weed species seeding rate at AB may have promoted more competition.

It is also important to note that in the current study, only semi-leafless field pea cultivars varying in traits known to confer competitive ability were utilized; not all semi-leafless field pea cultivars could be evaluated. More specifically, the selection of cultivars included commonly grown cultivars that exhibited varying combinations of vine length and seed size. This is novel because previous literature has not examined the competitive ability of semi-leafless field pea cultivars, nor has it examined the mechanism underlying differences in their ability to withstand and suppress competition. In addition, most literature on field pea competitive ability has involved eight or fewer field pea cultivars (Wall et al., 1991; McDonald, 2003; Harker et al., 2008; Spies et al., 2011; Vasilakoglou and Dhima, 2012). Most of the aforementioned studies included semi-leafless field pea cultivars that were evaluated against normal leaf or forage cultivars, which are known to have a higher competitive ability in the presence of weeds. We included only semi-leafless field pea cultivars in our study because they are preferentially grown over normal leaf cultivars due to their greater yield, lodging resistance, and reduced disease pressure (Heath and Hebblethwaite, 1985 b; May et al., 2003).

Results from this thesis show that some competitive differences do exist among semi-leafless field pea cultivars, though none of the above-ground traits measured in this study could be associated with these competitive differences. Cultivars did differ in their AC and AWC values, but these differences were not always consistent. For example, CDC Dakota ranked 1st for AC, but 7th for AWC, while CDC Sage ranked 4th and 9th for AWC and AC, respectively (Table 3.9). Watson et al. (2006) also noted discrepancies among barley cultivars in their AWC and AC ranking. In that study, Harrington ranked 8th and 17th for AWC and AC, respectively, while Candle, ranked 3rd and 17th for AWC and AC. Compared with the rankings of Watson et al. (2006), our results suggest that field pea shows less variation than barley for AWC and AC.

Another important aspect of this thesis was to assess the relative importance of both below and above-ground competition of field pea. For that reason, a greenhouse study was undertaken to provide the necessary conditions and combinations of competition regimes to provide insight into the importance of above- and below-ground competition. Understanding how a focal pea plant responds to intraspecific vs. interspecific competition above- and below-ground may be critical to breeding more competitive field pea cultivars. The greenhouse results revealed that the focal pea plant did not respond differently to interspecific and intraspecific competition. This suggests that field pea lacks a mechanism to recognize the identity of neighbouring plants. That is, field pea plants respond equally to neighbours of any species, whether that neighbour is another pea plant or a weed. Nevertheless, we did observe a significant increase in focal plant root biomass when shoot competition was permitted, demonstrating that the response to above-ground neighbours prompted greater root biomass accumulation. Although several studies have shown that plants respond to neighbours through changes in light quality (Rajcan and Swanton, 2001; Lie et al., 2009), our data suggests that it is unlikely that field pea plants use light to discriminate between neighbouring species. While we did observe greater root biomass allocation under shoot competition, this occurred regardless of the identity of the neighbouring plant. Therefore, selecting for plants that do not respond to, or respond less to changes in light quality may result in field pea crops that have a greater ability to withstand the presence of neighbours, regardless of whether they are neighbouring crop plants or weeds.

The greenhouse study also confirmed that below-ground competition is playing an important role in field pea competitive ability (Figure 4.7). Differences in below-ground competitive ability may be a response that is triggered by the above-ground sensing of neighbours. Cultivar performance in the field suggested that semi-leafless field pea cultivars exhibit differences in their competitive ability. However, results from the greenhouse study demonstrated the need for more research to identify the casual mechanism behind the changes in field pea root biomass and root to shoot allocation. Research by Walker and King (2009) found that minimizing root competition in the seedling phase would beneficial to establishing Kura clover. Cahill (2002) reported that root and shoot competition are connected; measuring only one of these two mechanisms of competition will convey little information about the relative importance of that mechanism. Yet Rajcan and Swanton (2001) noted that changes in light quality are used by plants to detect neighbours, and a recent study showed that corn (*Zea mays* L.) plants detected weeds by sensing changes in light quality (Liu et al., 2009). Further research is needed to examine the response of field pea to light quality and to determine exactly how, and if, these changes impact field pea competitive ability and resource allocation.

5.2 Management implications

In this thesis, we found that field pea cultivars differed in their ability to withstand and suppress competition from weeds. Producers who grow cultivars that have a poor ability to withstand competition need to ensure that preemergence herbicides are used to minimize early season losses from weeds. This may also involve applying herbicides in-crop to ensure the crop moves through the critical period of weed control with minimal competition from weeds. Ultimately, it is essential to maximize weed control and to minimize competition from weeds regardless of which field pea cultivar producers select. Yield losses from weed competition ranged from 9% to 38% in our study, which will substantially impact profitability. Optimal weed control should provide for a competitive field pea crop, and will help to minimize yield loss. Alternatively, organic growers may consider using cultivars that have the ability to smother weeds (AC) so as to minimize weed competition, thereby minimizing weed growth and potential increases to the weed seedbank.

Recommending cultivars based solely on the results of this study is difficult, as differences in competitive ability were small in magnitude and somewhat inconsistent. One must also consider other attributes of cultivars for selection in addition to competitive ability, and some traits may make cultivars less desirable for crop production. For example, although CDC Centennial and CDC Mozart exhibited some of the greatest AWC values, they were also severely lodged and thus, would not be recommended from a practical perspective. CDC Patrick, due to its ability to withstand model weed competition and reduce model weed seed production, would be an excellent cultivar to grow to help manage losses from weeds. CDC Dakota and CDC Meadow could also be recommended due to an excellent ability to supress model weed seed production and an intermediate ability to withstand model weed competition.

5.3 Future research

This research has provided an examination of semi-leafless field pea cultivar tolerance to and suppression of model weeds. Fourteen semi-leafless field pea cultivars were evaluated, of which four are obsolete and one is a forage cultivar. Studies such as this are always limited by cultivar inclusion and availability, and including more cultivars, especially new ones, will help producers decide which of these new cultivars are worth growing. In addition, this thesis identified competitive differences among semi-leafless field pea cultivars, although differences were only detected in three of five site-years. More research in different environments is needed to evaluate cultivars under varying types of abiotic stress.

This current study also noted that field pea plants did not exhibit a variable response to interspecific or intraspecific competition. Nevertheless, the focal pea plant responded significantly to root intermingling and shoot competition. More research is needed to identify which below-ground traits most influence field pea competitive ability and also, to determine the response of field pea to above-ground cues such as light quality (R:FR ratio). This research could lead to selecting for field pea cultivars that exhibit excellent abilities to compete below-ground, which may lead to improved competitive ability. In addition, determining how to predict field pea response to neighbours and how competition may differ between each cultivar would prove useful in choosing field pea cultivars.

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